agriloop

high-value products from agricultural residues through sustainable chains

Project number: 101081776

Deliverable D1.5

Second estimates of biomass residue volumes, composition, bio-based yields and environmental performances

Workpackage(s) concerned: WP1
Workpackage leader: Jan Broeze (WR)
Deliverable Leader: Jan Broeze (WR)
EC Version: 1.0

Planned delivery date (as in DoA): 30/11/2024 (M24)
Actual submission date: 30/11/2024, (M24)

Funded by the European Union

UK Research and Innovation

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

中华人民共和国科学技术部
Ministry of Science and Technology of the People's Republic of China

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This project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement No. 101081776, the UK Research and Innovation (UKRI) fund under the UK government's Horizon Europe funding guarantee, the Swiss State Secretariat for Education, Research and Innovation (SERI) and from the National Key Research and Development Program of China (NKRDPC). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of neither of the aforementioned Funding authorities. Neither the European Union, the United Kingdom, the Swiss Confederation or the People's Republic of China nor the European Commission, UKRI, SERI or NKRDPC can be held responsible for them.

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Other	(Please describe the type)	☐

Project Number: 10108176

Project: AgriLoop : pushing the frontier of circular agriculture by converting residues into novel economic, social and environmental opportunities

Topic: HORIZON-CL6-2022-CIRCBIO-01-05

Duration: 48 Months

Start date of Project: 1st December 2022

End date of the Project: 30 November 2026

Coordinator: INRAE

Deliverable: D1.5

Due date of deliverable: 30/11/2024

Actual submission date: 30/11/2024

Work package number: WP1

WP Leader (name and organisation): Wageningen Research (WR)

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Version: 1.0

Executive Summary

The goal of Agriloop task 1.2 is to generalize the quantitative findings from technological work packages (Agriloop WPs 2 and 3) to a broader range of agricultural residues and to underpin decision making. The ultimate objective is to promote sustainable practices, reduce waste, and contribute to the development of a circular (bio-)economy in Europe and China by optimising the use of agricultural residues for fulfilling the societal demand for food (proteins) and non-food products (like biopolymers).

In order to provide early assessments of valorisation options of agri-residues the dataset introduced in Agriloop deliverable D1.4 was further extended. Specifically:

- the set of selected agri-residues was extended with residue streams considered by the Agriloop-CN partners, including quantitative estimates per country (EU-27, UK and CN) and further completed macro-nutrient compositions,
- conversion and extraction efficiencies of processing/valorisation pathways (like anaerobic digestion, fermentation for bioethanol, PHA production and diverse protein extraction methods) were further quantitatively elaborated,
- a method for early assessing environmental impact (climate impact and degree of circularity) per valorisation option of a residue stream was developed, and first results are presented in this deliverable. In order to make comparisons with common valorisation pathways (like feed application), also such common pathways were described in this method.

From first case studies with the method for early environmental impact assessment, some preliminary general conclusions were drawn:

- Adequate combination of material – processing pathway – product application is essential for efficiency and environmental sustainability. Generated results confirm, for instance, that residue streams with relatively high protein content are more suited for protein extraction (or use as animal feed), whereas residue streams with high content of (simple) carbohydrates are more suited for producing biopolymers or other biobased applications.
- Although the utilisation of a residue stream is considered sustainable, energy use in intensive processing can have relatively large negative impact on the environmental sustainability of a processing route/application. This was illustrated for extracting rubisco proteins from sugar beet leaves. Preliminary assumed energy use in the extraction and further processing (estimated from one reference) results in higher GHG emission intensity of the rubisco protein product than a reference protein product considered (soybean protein isolate). From this observation it is concluded that making choices regarding the processing route, the impact of the (process) chain must also be taken into account.
  Note: the comparison of rubisco protein with soybean protein isolate overlooks functional differences between both products; it is recommended to extend the comparison with protein sources that are more similar. The example of rubisco protein extraction was provided here in order to show the relevancy of addressing all aspects of the pathway from residue to products.

In order to derive realistic heuristics for estimating yields to products through the diverse processing pathways analysed in the technological work packages (Agriloop WPs 2, 3 and 4), a modelling and optimisation tool was developed; first findings (on biorefinery of potato residues) are presented in this deliverable. In follow-up work, this approach will deliver heuristics for estimating practical yields to products in scope of Agriloop.

1 Introduction

Agricultural and food production practices are associated with considerable environmental burdens through the consumption of resources such as land, water, energy etc. and through the generation of large and diverse residue streams. Primary agricultural residues, generated close to the fields, are often dispersed, or left on the field, overlooking their potential contribution to a circular (bio-)economy. Often, leaving the residues on the field is considered essential for maintaining soil health/fertility. Secondary residues are available in large quantity on plant processing sites, where they are often destined to low-value applications or managed as waste.

The residue streams provide a large pool of largely underutilized resources (see e.g. Scarlat et al., 2019). Additional value (in terms of proteins, biopolymers, or other valuable product) can be generated from them. In many situations the residue of extracting valuable components from a primary residue stream may remain available for the purpose that the residues are used for (like soil application). Persistent fibre components and minerals will end in the residues, which is still functional for soil health.

This deliverable aims at generating a dataset estimating the volumes and compositions of major residues in Europe and China, together with potential extraction/conversion rates to biopolymers, proteins, and other value-added products, with the intention of screening the routes with a higher environmental performance. Consequently, the quantitative findings of the technological work packages (WPs 2 and 3) are generalized to a broad set of agri-residues, as pointed out in Agriloop milestone document MS-10. The results are a further iteration of the dataset and heuristics provided in Agriloop deliverable 1.4. Specifically, the following extensions are accomplished:

- The set of selected agri-residues was extended with residue streams considered by the Agriloop-CN partners, including estimates of volumes per country (EU-27, UK and CN). The estimates for primary residues were derived from crop production areas and volumes per country. The volumes of secondary residues were estimated from the main product volumes (like beer and wine) production per country. The used heuristics are presented in this deliverable.
- The macro-nutrient compositions were further completed, including the agri-residues in scope of CN Agriloop partners.
- Conversion and extraction efficiencies of processing/valorisation pathways (like anaerobic digestion, fermentation for bioethanol, PHA production and diverse protein extraction methods) were further quantitatively elaborated based on data obtained from scientific literature.
- A methodology for early assessing climate impact and degree of circularity per valorisation option of a residue stream was developed, and first results were added to the dataset. Heuristics were elaborated in an excel-based calculator, which facilitates rapid assessments of valorisation pathways based on a residue-stream's composition. In order to make comparisons with common valorisation pathways (like feed application), also such common pathways are described in the method.

Next to using knowledge on extraction and conversion processing from literature, this deliverable presents an approach for exploiting knowledge for extraction and conversion processes which are subject of technical research in the Agriloop project (Agriloop WPs 2, 3 and 4). These individual findings must be translated to complete (biorefinery) processing pathways. Since in defining a biorefinery processing pathway many degrees of freedom exist (think of selection of specific unit operations, unit processes order, processing conditions, etc.) which may affect the actual yield of conversion and extraction processes, it is essential to identify optimised processing pathways. Analysing and comparing diverse pathways is essential to identify which biorefinery designs are most promising for stakeholders that maximize or minimize specific objectives, such as economic returns and/or environmental benefits.

To address this goal, mathematical models can be developed that represent the sequential transformation and separation of agricultural residues into valuable products. More specifically, a superstructure model can be generated which is essentially a conceptual map that includes all possible processing pathways and their interconnections. The superstructure model allows for a systematic evaluation of different design options and facilitates a comparison of alternatives to identify the most cost efficient, sustainable, or feasible solutions. The developed method and first findings (on biorefinery of potato residues) are presented in this deliverable. In follow-up work, this method will provide heuristics for estimating practical yields to products in the scope of Agriloop.

2 Data collection on agri-residues compositions

2.1 Selected agri-residual streams

The selection of primary agri-residues streams was based on an analysis of main crops in the EU (Agriloop D1.4) and extended with crop residue stream in scope of CN partners (rice straw):

- wheat straw
- maize (or corn) stover
- barley straw
- rye straw
- oat straw
- triticale straw
- rice straw
- tomato crop residues
- grape branches and leaves
- rapeseed straw
- sunflower stalks (straw)
- olive tree pruning branches,
- olive leaves
- potato crop residues
- sugar beet leaves

The selection of secondary residues and reject product proposed in Agriloop D1.4 was extended including selected secondary residues by Chinese Agriloop partners (next to some streams already in scope of the EU partners, specifically residues from peanut and rice processing were added):

- apple pomace
- brewer's spent grain
- brewer’s yeast
- distillers grains (ddgs) from maize
- distillers grains (ddgs) from wheat
- grape pomace
- grape seeds
- olive pomace
- olive stones
- peanut meal
- peanut skins
- potato peels
- potato pulp (from potato starch industry)
- rice (broken rice, discoloured rice, unripe rice)
- rice bran
- rice bran, defatted
- rice husk

- sugar beet molasses
- sugar beet pulp
- tomato pomace
- tomato skins

2.2 Estimates of average composition and other characteristics of selected agri-residual streams

Estimates of macro-nutrient composition of the residues were derived from various information sources, especially Feedipedia.org, CVB (2023) and Madbarn.com. In case of multiple entries for a residue stream (CVB for some residue streams distinguishes specific streams with different protein or fibre content) the average of listed streams was taken.

For a large number of streams, the data provided by an information source was not covering all macro-nutrients; for such streams information from these datasets were combined, estimates from a similar stream were assumed adequate (e.g. some lacking details for various straws were taken from wheat straw) or other complementary information sources were used:

- for potato crop residues: Zwart et al. (2004), Salehi et al. (2014), Kolbe et al. (1997) and Soltaninejad et al. (2022),
- for sugar beet leaves: Aramrueang et al. (2017), Tamayo Tenorio (2017), Wadhwa et al. (2005),
- for olive stones: Maestri et al. (2019),
- for tomato skins: Toscano et al. (2015),
- for grape pomace and grape seeds: Ladakis et al. (2020),
- for peanut skins: data from IFST-CAAS (Hui Hu), presented in the Agriloop Annual Meeting, March 2024,

In order to enable (sustainability impact) comparison with common uses of the agri-residues, also data on nutritional feed energy for the most common livestock animals were collected: VEM[1] (for dairy cattle), NE2015 (estimator for nutritional energy for pigs) and Energy value for layer chicken. The values were either directly obtained from Feedipedia.org or CVB, or estimated with heuristics presented by Broeze et al. (2024). Remark: not all residue streams are suitable for each livestock animal; however, still the estimated nutritional energy values is listed.

The complete overview of collected compositional and feed-energy information is presented in Table 1. In this table residues with high content of simple carbohydrates (approximately or larger than 50%) and with high content of proteins (>30%) are highlighted; these are from a content perspective most interesting for protein and biopolymer production.

[1] Dutch feed energy system translating to "Feed Unit Milk", which is a dimensionless energy parameter for dairy farmers. It represents the relative net energy content of a product for lactating cows per energy content of 1 kg of standardized barley (barley with a specific hectolitre weight and starch content, etc.). By definition, the energy content of this kg of barley is set at 1,000 VE. The Feed Unit Milk is calculated based on the level of digestible crude protein, digestible organic matter, digestible crude fibre, digestible crude fat and digestible carbohydrates (sugar, starch, other carbohydrates) (source: https://www.eurofins-agro.com/en/feed-energy---dutch-system).

TABLE 1. COLLECTED MACRO-NUTRIENT COMPOSITION AND FEEDING VALUE ESTIMATES OF SELECTED AGRI-RESIDUES (RESIDUES STREAMS WITH RELATIVELY HIGH CONTENT OF SIMPLE CARBOHYDRATE CONTENT OR PROTEIN CONTENT ARE HIGHLIGHTED).

Residual stream	*DM content (g/kg)*	*Org. M (g/kg DM).*	*Ash (g/kg DM)*	*Protein (g/kg DM)*	*Lipids (g/kg DM)*	*Lignin (g/kg DM)*	*Cellulose (g/kg DM)*	*Hemi-cell. (g/kg DM)*	*Starch (g/kg DM)*	*Sugar (g/kg DM)*	*Others (g/kg DM)*	*VEM*	*NE2015 (kJ/kg)*	*Energy Layer Chicken (kJ/kg)*
Wheat straw	907	931	69	45	15	76	471	270	17	16	21	595	6017	2336
Barley straw	909	925	75	38	14	65	418	322	10	12	46	595	6235	2407
Oat straw	896	921	79	39	16	69	402	292	12	32	60	608	6293	3116
Rye straw	920	923	77	41	14	90	413	276	10	12	67	581	5778	2824
Maize (corn) stover	296	932	68	68	18	56	340	303	10	12	125	650	6887	4471
Rice straw	928	819	181	42	14	48	376	267	10	12	50	543	5755	2548
Sunflower straw	898	883	117	73	14	66	390	250	10	12	68	593	6041	3420
Rapeseed straw	921	930	70	57	14	130	459	153	3	12	102	565	4989	3598
Tomato crop residues	563	945	55	46	17	171	189	121	10	12	379	611	5222	8435
Grape branches and leaves	563	945	55	46	17	171	189	121	10	12	379	611	5222	8435
Olive pruning leaves	501	910	90	98	-	201	140	120	-	-	351	553	4136	7846
Olive pruning branches	898	928	72	78	-	179	208	138	-	-	325	557	4443	7035
Potato crop residues	187	845	155	73	19	203	355	134	16	36	8	499	3472	3096
Sugar beet leaves	120	811	189	195	24	46	130	145	45	161	64	844	7645	9134
Sugar beet tops	279	859	141	116	13	55	155	137	18	76	87	658	6750	9230
Triticale straw	240	956	44	250	92	58	160	286	26	13	71	904	6827	9981
Broken rice	885	993	7	78	8	5	8	22	715	9	148	1078	11410	14800
Discolored rice	883	949	52	78	20	54	70	108	561	13	45	825	8490	11250
Unripe rice	883	949	52	78	20	54	70	108	561	13	45	825	8490	11250
Brewer's spent grain	240	956	44	250	92	58	160	286	26	13	71	904	6827	9981
Brewer's yeast	907	938	62	383	84	33	142	54	94	30	119	909	7810	10920
Rice husk	919	825	175	37	-	142	375	161	53	-	57	467	3785	2572
Rice bran	905	894	106	126	138	58	109	135	270	26	33	1086	10075	13315
Rice bran, defatted	901	848	152	133	33	75	144	150	243	24	45	792	6867	9089
Olive pomace	885	920	80	123	42	244	179	127	-	43	162	637	4626	7399
Olive stones	879	973	27	172	304	-	-		21	-	476	1506	17301	23514
Tomato pomace	935	948	52	210	119	254	189	106	-	-	70	846	6883	9619
Tomato skins	900	978	22	119	31	491	225	48	-	-	64	448	15	4458
Grape pomace	397	922	79	148		298	148	116	18	142	52	567	2964	6335
Grape seeds	450	920	46	91	114	332	201	161	9		11	688	4691	6408
Potato peels	142	937	63	127	10	13	53	33	476	15	212	1094	11230	14826
Potato pulp (starch industry)	156	947	53	95	2	49	113	170	208	11	300	1025	8099	10787
Grey starch	380	955	45	104	13	-	-	-	590	27	222	1062	11263	12830
Apple pomace	208	1111	25	68	42	157	185	109	-	62	352	739	6000	10027
Sugar beet pulp	248	923	77	82	8	9	220	251	10	53	290	932	9060	7903

Residual stream	*DM content (g/kg)*	*Org. M (g/kg DM).*	*Ash (g/kg DM)*	*Protein (g/kg DM)*	*Lipids (g/kg DM)*	*Lignin (g/kg DM)*	*Cellulose (g/kg DM)*	*Hemi-cell. (g/kg DM)*	*Starch (g/kg DM)*	*Sugar (g/kg DM)*	*Others (g/kg DM)*	*VEM*	*NE2015 (kJ/kg)*	*Energy Layer Chicken (kJ/kg)*
Molasses	787	910	90	98	2	-	-	-	-	512	298	805	7310	8430
Defatted peanut meal (from mechanical extraction)	900	945	55	530	11	8	55	14	118	144	22	1063	10180	14902
Defatted peanut meal (from solvent extraction)	920	933	67	489	16	14	49	77	110	134	33	1052	10226	14236
Peanut meal	910	939	61	510	14	11	52	46	114	139	28	1057	10203	14569
Peanut skins	913	961	39	164	199	128	186	75	175	33	2	1190	12008	14316
Rice	885	993	7	78	8	5	8	22	715	9	148	1078	11410	14800
DDGS from maize	903	956	44	268	125	35	84	169	29	17	229	1182	9240	14449
DDGS from wheat	916	954	46	324	68	77	89	139	11	49	197	1071	7420	12933

3 Estimations of yields to biopolymers, proteins and other biobased products

Yields of extraction and conversion pathways from agricultural residues to biopolymers and protein products are estimated through heuristic rules. These rules describe mass balances, based on macro-nutrient composition of the agricultural residues.

For the conversion processes addressed in this deliverable, rules derived from literature study were used.

3.1 Typical yield factors for production of biofuels, chemicals and plastics

Through fermentation and other conversion processes, nutrients can be converted to various biobased materials. Yield factors in general vary amongst processing pathways. Estimated yield factors for a set of common pathways/products are summarized in Table 2 and Table 3. These tables give theoretical potentials (estimated from stoichiometry of the main chemical reactions for a representative molecule per macro-nutrient category) and practical yields, estimated from published results.

TABLE 2. MACRONUTRIENT YIELD FACTORS TO ENERGY CARRIERS, KG PRODUCT PER KG FEEDSTOCK (T: THEORETICAL, POTENTIAL YIELD DERIVED FROM AMONGST OTHERS STOCHIOMETRICS; P: PRACTICAL/TYPICAL VALUES, OR RANGE OF VALUES, DERIVED FROM REFERENCES[2]).[3]

Macro-nutrient Product	Biomethane	Bio-ethanol (fermentation)	Bio-ethanol (BTL) (pyrolysis or Fisher Trops)	Biodiesel (FAME)	Biodiesel (HVO)
Protein	0.34 (T)[a] 0.33 (P)[a]				
Lipids	0.72 (T)[a] 0.56 (P)[a]			1.0 (T)[a] 0.96 (P)[a]	0.75 (P)[a]
Sugar	0.27 (T)[a] 0.26 (P)[a]	0.51 (T)[a,d] 0.47 (P)[a]	0.27(P)		
Starch	0.27 (T)[a] 0.26 (P)[a]	0.57 (T)[d] 0.42 (P)[a]	0.27 (P)		
Cellulose	0.30-0.35 (T)[a,b] 0.18-0.25 (P)[a,b,c]	0.51-0.57 (T)[a,e] 0.35-0.38 (P)[a]	0.12 (P)		
Hemicellulose	0.29 (T)[b] 0.13-0.16 (P)[b]	±0.4 (T)			
Lignin[4]					

[2] References: [a] Nova (2015); [b] Li et al. (2018); [c] Golkowska et al (2013); [d] eubia (2022); [e] Sadhukhan et al. (2019); [f] Lovett et al. (2016); [g] IfBB (2021); [h] Burniol-Figols et al. (2018) ; [i] Sohail et al. (2020)

[3] These conversion factors are for 'first generation-technologies' for non-lignocellulose feedstocks. Higher conversion factors can be obtained from especially lignocellulose feedstocks with second generation processes.

[4] Generally lignin is considered not digestible in biological conversion processes.

TABLE 3. MACRONUTRIENT YIELD FACTORS TO BIOPOLYMERS, KG PRODUCT PER KG FEEDSTOCK (T: THEORETICAL, POTENTIAL YIELD DERIVED FROM AMONGST OTHERS STOCHIOMETRICS; P: PRACTICAL/TYPICAL VALUES, OR RANGE OF VALUES, DERIVED/ESTIMATED FROM REFERENCES[2]).

Products Macro-nutrient	Bio-PE	Bio-PET (30%)	PLA	PEF	PHA/PHB
Protein					
Lipids					0.35[h,i]
Sugar	0.25-0.29 (P)[a,f,g]	0.20[g]	0.68 - 0.80 (T)[a,g] 0.67- 0.77 (P)[a,g]	0.56 (T)[a] 0.51-0.55 (P)[a]	0.35 - 0.48 (T)[a,g] 0.40 (P)[g]
Starch	0.20 (P)[g]		0.60 (P)[g]		0.31 (T)[g]
Cellulose					
Hemicellulose					
Lignin					

Note: for cellulose, hemicellulose, lignin and other carbohydrates no conversion factors were found.

Remark: with second generation technologies large part of cellulose and hemicellulose may be converted to sugar and consequentially have substantial yield to biopolymers. These are not represented here.

Based on above, combined with estimates from Bos & Sanders (2013), typical/average conversion yields are presented in below table.

TABLE 4. ASSUMED AVERAGE MACRONUTRIENT CONVERSION FACTORS, KG PRODUCT PER KG COMPONENT IN THE FEEDSTOCK.

Macro-nutrient Product	Biomethane	Bio-ethanol (fermentation)	Bio-ethanol (BTL) (pyrolysis or Fisher Trops)	Biodiesel	PLA	PHA/PHB
Protein	0.33					
Lipids	0.56			0.9[5]	0.75	0.35
Sugar	0.26	0.5	0.27		0.6	0.4
Starch	0.26	0.5	0.27			0.35
Cellulose	0.20	0.4	0.12			
Hemicellulose	0.15	0.3				
Lignin						
Other carbohydrates[6]	0.22	0.43	0.22			

Estimates of yields to the products for the selected residue streams (based on residue compositional information as presented in chapter 2) are presented in Annex 1.

3.2 Typical yield factors for protein extraction methods

A broad variety of extraction pathways for proteins from organic materials exist, varying from low-yield processes (possibly resulting in relatively pure, dedicated protein products) to high-yielding processes (resulting in bulk proteins), see e.g. Voudouris et al. (2017).

[5] Assumed oil extraction efficiency of 95%.

[6] Diverse other categories of carbohydrates, generally more resistant than sugar and starch, but less than (hemi-)cellulose.

Typically, through alkaline or enzymatic hydrolysis, approximately up to 70% of proteins can be extracted (estimated from Estimated from Da Fonseca et al (2023), Uddin et al. (2018) and Voogt et al. (2021).

Cosun (2019) provides some insights in realistic yields of the high-value protein Rubisco from beet leaves: approximately 30% of the proteins from the sugar beet leaves can be obtained in the Rubisco extract.

Estimates of extraction yields for the selected residue streams (based on residue compositional information as presented in chapter 2) are presented in Annex 1.

3.3 Estimating yields to biopolymers and proteins for Agriloop processing pathways

A few products in scope of the technological research of Agriloop were already introduced in previous sections (amongst which PHA/PHB, proteins). Currently, diverse dedicated pathways for extracting proteins and producing biopolymers are subject of technological research. Based on modelling and optimisation of such pathways (see chapter 6), conversion factors for a selected set of pathways will be estimated; these will be presented in Agriloop deliverable D1.6.

4 Methodology development of early estimates of environmental performance

Two indicators are selected in this study:

- Indicator for environmental sustainability impact: effects on greenhouse gas (GHG) emissions
- Indicator for resource use efficiency: circularity

The elaboration of these indicators contributes to the aim of the European Commission (EC, 2020) to achieve climate neutrality, for which synergies between circularity and reduction of greenhouse gas emissions need to be stepped up, specifically through

- analysing how the impact of circularity on climate change mitigation and adaptation can be measured in a systematic way;
- improving modelling tools to capture the benefits of the circular economy on greenhouse gas emission reduction at EU and national levels of EU countries, UK and CN.

In the assessment of environmental performance, next to the main/intended products, also possible co-products must be addressed. In the actual version of the method a number of common processing/application pathways are addressed, including a few pathways (introduced in Chapter 3) based on insights derived from literature (Table 5).

Ongoing research in Agriloop (technical work packages, combined with the approach introduced in chapter 6 of this report) will provide parameters for early estimating environmental impacts of new pathways. This will be reported in the following Deliverable 1.6.

TABLE 5. CONSIDERED MAIN AND CO-PRODUCTS FOR A SUBSET OF THE PROCESSING/APPLICATION PATHWAYS ELABORATED IN CHAPTER 3

Processing/application pathway	Considered <u>products</u> and co-products and their destinations / functions
directly applied or left behind in the field	<u>"Fertilizer"</u>: • N: fertilizer nutrient (replaces synthetic fertilizer) • Persistent organic matter: contributes to physical soil fertility + carbon sequestration
feed (dairy cattle, pigs, layer hens, broilers)	<u>food</u> (replaces, based on ratio of nutritional energy and protein content, wheat and soybean protein isolate in food) manure: applied to the soil (fertilizer, see above)
anaerobic digestion	<u>bio-methane</u> digestate (utilized as fertilizer)
PHA/PHB production	<u>PHA/PHB</u> biogas digestate (utilized as fertilizer)
Alkaline protein extraction	<u>food ingredient</u> biogas digestate (utilized as fertilizer)

Enzymatic protein extraction, combined with fermentative ethanol production	food ingredient (protein product is assumed to replace soybean protein isolate) bio-ethanol feed (which again results in food and manure, see above)
Rubisco protein extraction	food ingredient (protein product is assumed to replace soybean protein isolate) biogas (replaces natural gas) digestate (utilized as fertilizer)

4.1 Generic approach: estimating effects on GHG emissions

System expansion, which is very common in LCA's. This means that the following elements are taken in consideration:

- GHG emissions associated to the processing of the residue stream, including:
  - GHG emissions associated to used energy,
  - GHG emissions associated to auxiliary inputs/materials,
  - direct emissions of other GHG gasses,
- effects of deriving the residue from their common use or waste management,
- effects of replacing common products (food, feed, fossil-derived materials or fuels) by the products and co-products generated from the agri-residue.

Energy use (fuels and electricity) in processing are derived from literature or estimated from unit operations conditions. For fuels fixed GHG emission factors can be applied for all countries; for electricity dedicated GHG emission factors can be used per country (or EU-average for EU countries).

GHG emissions due to auxiliary inputs and emissions of other GHG gasses are neglected, unless the cases for which specific information is provided or found in literature.

A first inventory of specific factors for estimating GHG emission of processing pathways proposed in Chapter 3 was made through a literature scan; these preliminary results are presented in Table 6.

TABLE 6. COLLECTED FACTORS FOR FIRST ESTIMATES OF GHG EMISSIONS ASSOCIATED TO PROCESSING STEPS IN VALORISATION PATHWAYS

Process	Result	Reference
Energy use in anaerobic digestion for biogas production	9 kWh electricity and 550MJ heat per ton substrate	Estimated from Lijo et al., 2014
Energy use in biogas upgrading	700 kWh per ton methane	Estimated from Francisco López et al. (2024)
Methane leakage in anaerobic digestion	2% of produced methane	Estimated from Francisco López et al. (2024)
Enzymatic protein extraction	177 kWh electricity and 7880 MJ heat per ton material	Estimated from Voogt et al. (2021)
Bioethanol fermentation	44 kWh electricity and 6020 m^3 natural gas per ton material	Estimated from Voogt et al. (2021)
Energy use in PHA production	1.3 kWh and 16.5 MJ heat per kg PHA produced	Estimated from Saavedra del Oso et al., (2023) (to be updated with anticipated results from AgriLoop WP4).

The effect of replacing a common product through the product and co-products derived from the agri-residue is estimated as explained in Annex 3.

Effects of deriving the residue from their common uses are likewise estimated, for the common uses. In order to practically enable this, next to 'new' processing pathways also common application/processing pathways are modelled (see Annex 3), e.g.

- leaving (crop residues) in the field ('soil application', with fertilizer functionality),
- anaerobic digestion,
- feed for cattle,
- feed for pigs.

4.2 Generic approach: estimating circularity

A broad set of metrics for circular economy (CE) have been defined, mainly addressing environmental, economic and social issues. Most indicators focus on recycling, linking to resource-use efficiency (Vural Gursel et al., 2023).

For monitoring circularity Eurostat has developed the 'circular material use rate' — in short 'circularity rate' — which measures the contribution of recycled materials towards the overall use of materials[7]. The circularity rate is the share of material resources used in the EU which came from recycled waste materials, thus saving primary raw materials from being extracted.

For organic residue streams the material that is used as food and fodder is considered 'circular material use', and the share of residue streams in food and fodder of the total food and fodder use is counted as 'circularity rate'.

The 'circularity rate' has some drawbacks, related to the inherent transformation and degradation of organic molecules in production and consumption:

- Use for food and fodder are equally appreciated in the 'circularity rate'. This may seem logical from the market-demand perspective, but disregards that the resource use efficiency to food is significantly affected by the limited protein and energy conversion efficiency of livestock. This is underpinned by the food waste hierarchy (European Parliament Council, 2008; Papargyropoulou et al., 2014; Teigiserova et al., 2020), which appreciates use for food higher than use for fodder.
- In transformations of organic material to food or feed losses may occur (e.g. in extraction processes); this seems not explicitly incorporated in the 'circularity rate' assessment.
- The functionality of (components in) a residue stream in the application may vary amongst different applications. For example, a stream that has high lignocellulose content is less suitable for pig feed than for dairy feed.
- This approach neglects that also in other applications (e.g. when applied to the soil), a residue stream may contribute to crop production (through the supply of nutrients and persistent organic matter).
- Valuable non-food uses are also overlooked by the indicator.

[7] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Circular_economy_-_material_flows#Circularity_rate (accessed 18 October 2024).

After Vural Gursel et al. (2023): for increasing circularity of biomass use it is essential to monitor quality and to incorporate quality aspects in circularity evaluation. Here, quality refers to the potential resource utility or functionality based on the inherent and intrinsic material properties such as structure and chemical composition.

We propose to assess the 'degree of circularity' of a biomass valorisation pathway through a perspective that appreciates quality/functionality of the biomass in an application (introduced by Broeze et al., 2024). For that we propose to estimate the 'degree of circularity' as the contribution efficiency to final products. Here, 'final products' refers to food or biobased products; other applications (like feed, substrate for fermentation, etc.) are considered intermediate steps towards generation of the final products. Applications with highest 'degree of circularity' are promoted by this indicator.

> This perspective is largely consistent with Eurostat's 'circular material use rate' for fossils. This is because their contribution ratio to final products is proportional with their substitution ratio for material resources.

In this accounting, as in LCAs, a sufficiently broad scope is required. The uses of side streams from processing/valorisation pathway may also contribute to final product generation (Figure 1).

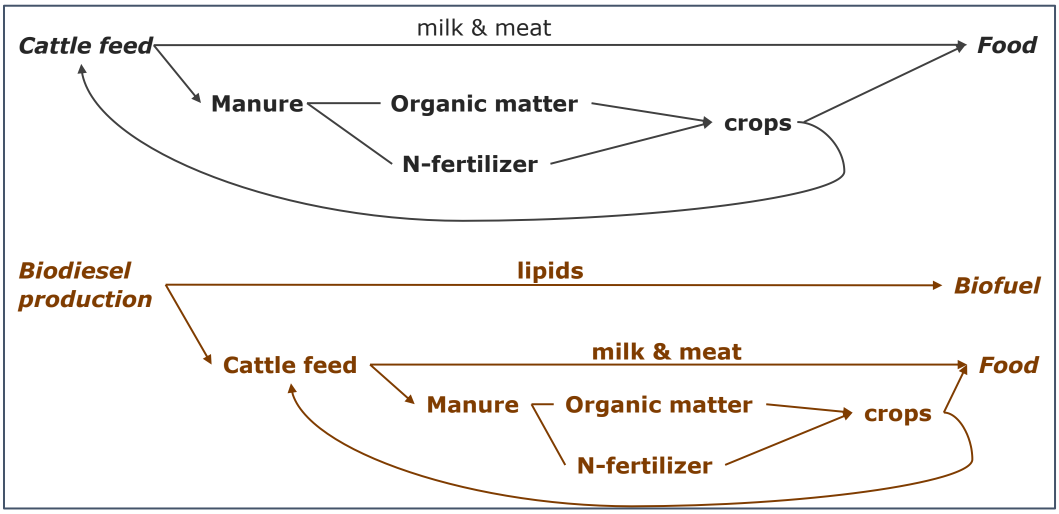

FIGURE 1. EXAMPLES OF DESTINATIONS IN VALORISATION PATHWAYS THAT MUST BE INCLUDED IN (EARLY) ENVIRONMENTAL IMPACT ANALYSES.

A formula expression for the degree of circularity:

$$Degree\ of\ circularity = \frac{\sum_{final\ products\ j} \sum_{components\ i} \left(Yield_{i,j} \times Appreciation_{i,j}\right)}{\sum_{components\ i} \left(Content_i \times Appreciation_{i,food}\right)}$$

In this formula, different macro-nutrients are appreciated differently. Default *Appreciation* of a macro-nutrient is the specific heat of combustion (reflecting the relevancy of energy in food, feed and many energy/fuel transformations). We have identified a small number of exceptions on this default rule:

- Proteins are appreciated higher in food and feed for diverse (correlated) reasons:

- In crop production systems, proteins have largely lower productivity per hectare than 'energy macronutrients'.
- Feed prices are largely determined by the protein content. This is quantitatively explained by wur.nl[8] who give quantitative insights in the price supplement of protein in dairy feed: between 2013 and 2023 this ratio varied from approximately 3 to almost 10.

Based on this, it was decided to appreciate protein at 4 times the value of carbohydrates.

- The market for substrate for biogas production competes with feed; commonly the lowest quality is acquired for this purpose. Considering that energetic conversion rate of sugar and oil to food by livestock is around 0.25 to 0.35 MJ/MJ, and in anaerobic digestion the energetic conversion rates are estimated between 70 and 75%, the market price situation can be reflected by appreciating biomethane value at less than 33% of that for food. With lack of further quantitative underpinning, for the time being biomethane is appreciated at 25% relative to food.

Remark: in practice all application/processing pathways have net efficiency lower than 100% (except for direct food application). Consequentially the calculated degree of circularity degree of all applications will be (substantially) lower than 100%. Striving for 100% degree of circularity is not reasonable; the indicator 'degree of circularity' can be used to compare different potential processing/application pathways but not for absolute evaluation.

For the quantitative assessments, heuristics of Broeze et al. (2024) were adopted. For some pathways updates (based on progressing insights) were applied:

- for soil application of organic material (like crop residues and methane): the contribution to food production via persistent organic matter was adjusted;
- diverse valorisation pathways (a subset of those presented in chapter 3) were added.

4.3 Preliminary results: comparisons of estimated environmental impact of different valorisation pathways

Below, the environmental impact of different valorisation pathways for three residue streams are compared. Table 7 and Table 8 present calculated synergies between reduction of greenhouse gas emissions and degree of circularity related to residue valorisation pathways for brewers' spent grain and grey starch, respectively.

Provisions:

- The results are preliminary; parameters are subject to update based on anticipated new insight. For instance, for many processing pathways GHG emissions related to the processing were estimated from limited literature sources that largely rely on small-scale experiments; these impacts may be substantially altered in upscaled systems; this will be further explored in the forthcoming project phase.

[8] https://www.wur.nl/nl/onderzoek-resultaten/onderzoeksinstituten/livestock-research/producten/voederwaardeprijzen-rundvee.htm

- In this comparison it is overlooked that some processing/application pathways are technologically hindered by characteristics of the feedstocks or that (bio-)availability of components in the materials may be low.

TABLE 7. SYNERGIES BETWEEN REDUCTION OF GREENHOUSE GAS EMISSIONS (KG CO_2-EQ. PER KG DRY MATTER VALORISED RESIDUE) AND DEGREE OF CIRCULARITY RELATED TO RESIDUE VALORISATION PATHWAYS FOR BREWERS' SPENT GRAIN

Product & co-products	Associated net GHG emissions savings	Degree of circularity	GHG emissions savings	Degree of circularity
			Benefit relative to Reference application	
Reference application: feed for cattle				
Food (replace feed)	1.2	0.21		
Manure: N		0.07		
Manure: organic matter		0.07		
TOTAL	1.2	0.35		
PHA/PHB production				
PHA/PHB	0.14	0.04		
PHA/PHB process energy use	-0.08			
Bio-methane (incl. CH4-em.)	0.50	0.06		
Digestate: N	0.17	0.08		
Digestate: organic matter	0.02	0.07		
Digestate: N_2O + CH_4 emissions	-0.15			
Digestate: carbon sequestration	0.18			
TOTAL	0.79	0.26	-0.41	-0.09
Enzymatic production of protein and bioethanol				
Food (protein product)	1.7	0.45		
Bioethanol	0.5	0.06		
Food (from cattle, replace feed)	0.23	0.07		
Manure: N		0.02		
Manure: organic matter		0.06		
TOTAL	2.4	0.66	1.2	0.21

Apparently, for the brewers' spent grain PHA/PHB production is not a very sustainable application, whereas protein extraction combined with bioethanol production seems more sustainable than the current use. This is consistently concluded from both sustainability indicators.

TABLE 8. SYNERGIES BETWEEN REDUCTION OF GREENHOUSE GAS EMISSIONS (KG CO_2-EQ. PER KG DRY MATTER VALORISED RESIDUE) AND DEGREE OF CIRCULARITY RELATED TO RESIDUE VALORISATION PATHWAYS FOR GREY STARCH

Product & co-products	Associated net GHG emissions savings	Degree of circularity	GHG emissions savings	Degree of circularity
			Benefit relative to Reference application	
Reference application: feed for cattle				
Food	0.45	0.25		
Manure: N		0.04		
Manure: organic matter		0		
TOTAL	0.45	0.29		
PHA/PHB production				
PHA/PHB	0.67	0.28		
PHA/PHB process energy use	-0.36			
Bio-methane	0.20	0.04		
Digestate: N	0.07	0.05		
Digestate: organic matter	0	0		
Digestate: N_2O + CH_4 emissions	-0.10			
Digestate: carbon sequestration				
TOTAL	0.51	0.37	0.06	0.08
Enzymatic production of protein and bioethanol				
Food (protein product)	0.36	0.27		
Bioethanol	-0.02	0.04		
Food (via cattle)	0.10	0.03		
Manure: N		0.01		

Manure: organic matter		0		
TOTAL	0.45	0.34	0.00	0.05

Apparently, for grey starch, from both sustainability indicators perspective PHA/PHB production is the preferred valorisation pathway.

TABLE 9. SYNERGIES BETWEEN REDUCTION OF GREENHOUSE GAS EMISSIONS (KG CO_2-EQ. PER KG DRY MATTER VALORISED RESIDUE) AND DEGREE OF CIRCULARITY RELATED TO RESIDUE VALORISATION PATHWAYS FOR SUGAR BEET LEAVES

Product & co-products	Associated net GHG emissions savings	Degree of circularity	GHG emissions savings	Degree of circularity
			Benefit relative to Reference application	
Reference application: left behind in the field/soil				
Fertilizer: N	0.08	0.05		
Fertilizer: organic matter	0.21	0.08		
N_2O emissions	-0.13			
TOTAL	0.16	0.14		
Feed for cattle				
Food	0.93	0.23		
Manure: N		0.07		
Manure: organic matter		0.07		
TOTAL	0.93	0.37	0.77	0.23
Enzymatic production of protein and bioethanol				
Food (protein product)	1.19	0.45		
Bioethanol	0.24	0.06		
Food (via cattle)	0.19	0.05		
Manure: N		0.02		
Manure: organic matter		0.06		
TOTAL	1.62	0.63	1.46	0.39
Rubisco protein production				
Food (Rubisco protein product)	0.67	0.17		
Rubisco extraction energy use	-0.94			
Biomethane	0.54	0.09		
Digestate: N	0.09	0.06		
Digestate: organic matter	0.02	0.06		
Digestate: N_2O + CH_4 emissions	-0.10			
Digestate: carbon sequestration	0.10			
TOTAL	0.38	0.37	0.22	0.23

For sugar beet leave valorisation the results may seem a bit surprising:

- The valorisation of cattle feed seems more sustainable than leaving the material behind in the field. This can be explained by 2 reasons:
    1. N from manure is better available for crops than N from crop residues that are left in the field, because a large fraction of that N can leach from the material during autumn and winter time.
    2. The most persistent fraction of the organic matter ends in the manure.

  Use for cattle feed is not common for a practical reason: it affects the taste of milk.

- The biorefinery process (enzymatic production of protein and bioethanol, residue for feed) appears most sustainable. It seems more sustainable than Rubisco protein extraction because:
    1. The protein extraction rate of the biorefinery process is substantially higher than in the Rubisco extraction process. Although the functionality of the Rubisco protein product is higher than the bulk protein product, they are both compared with soybean protein concentrate in the current version of the method. In order to make a fairer comparison, a further refinement of

data in the method is necessary (with more adequate replacement protein product).

2. The reference information for Rubisco extraction (Cosun, 2019, Skunca et al., 2021) mention substantial energy use in processing. GHG emissions related to that energy use are higher than the GHG emission reduction through replacing the equivalent volume of soybean protein isolate in food.

Some (preliminary) generic conclusions based on above case studies:

- The right choice of material – processing pathway – product application is crucial for efficiency and environmental sustainability.
- Although the utilisation of a residue stream is generally considered sustainable, energy use in intensive processing can have a relatively large negative impact on the environmental sustainability of the processing route/application. When making choices regarding the processing route, the impact of the process chain must also be taken into account.
- The environmental impact of a valorisation option can be significantly influenced by the possibilities and limitations for applications of process residues. These potential applications should be included in the sustainability evaluation of alternative valorisation options.

5 Estimations of volumes of agri-residual streams per country

In order to estimate theoretical potentials to final product, the volumes of selected agri-residual streams per country are quantified. This chapter presents updated results of those presented in Agriloop deliverable D1.4.

To estimate the volumes of the residual streams at country level, different approaches for the agricultural residues (primary residues) and processing residues (secondary residues) were used. For the primary residues, we estimated the volume of residues from crop production areas and volumes per country to estimate the yield of residues per country. For the secondary residues, to estimate the volume of residual streams per country, either direct data on residue generation were used or the residue volumes were estimated from residue factors gathered for each type of residue in combination with production volumes.

Total estimated volumes per residue stream per country are presented in Annex 2.

5.1 Estimations of agri-residues volumes from primary production

The amount of residues generated in the field is directly related to crop production area, and may depend on various factors; here it is assumed that the only relevant factor is the actual crop yield.

The foundation for estimating the volumes of above-ground crop residues is the widely accepted studies of Fischer and co-workers (Fischer et al. 2007, Fischer et al. 2009 and Fischer et al. 2010) and Scarlat et al. (2010).

Because of high variance/poor correlations in the expressions we have reviewed publications citing their work to understand, extend and include the involvement of other complementary parameters and dependencies such as factors influencing the yield.

Other more recent studies have used, verified and extended this work (e.g. García-Condado et al. 2019, García-Galindo et al. 2019).

Large variations were found for actual estimates between the heuristics by the different references. Based on comparisons with different practically reported residue yields, a heuristic that provides reasonable values was chosen.

For many crops only a limited fraction of the total crop residues can be harvested, e.g. crop residues for cereals consist of roots, stubble and straw; in the current practice only the straw fraction is harvested. Estimates for the fraction of crop residues that actually can be harvested are mentioned by amongst others:

- Scarlat et al. (2010):
  Sustainable removal rates: 40% for wheat, barley, rye and oats, 50% for maize, rice, rapeseed and sunflower,
- Scarlat et al. (2019):

Technical potential: 58% for wheat, barley rye, oats, and rice, 64% for maize, 50% for rapeseed, 52% for sunflower

- Sustainable removal rate: average for EU estimated at 42% (variable, based on local considerations)
- Selin Noren et al. (2022):

  Technical removal rates around 70% for wheat and 60% for barley.

Here, the technical potential removal rates proposed by Scarlat et al. (2019) are used; for other crop residues the technical potential is assumed 100%.

Table 10 presents the selected heuristics for estimates of technical potential of crop residue volumes.

TABLE 10. CORRELATIONS DERIVED FROM LITERATURE FOR THE VOLUME OF PRIMARY RESIDUES (TECHNICAL POTENTIAL TON DRY MATTER PER HA) RELATED TO CROP YIELD (Y: TON, AS-IS, PER HA).

Crop	Crop residue	Estimate of residue volume per ha	Specific reference
Wheat	*Wheat straw*	$0.58 \times 0.85 \times 2.125 \times Y^{0.6}$	Scarlat et al. 2010
Maize	*Maize (or corn) stover*	0.64 × 0.70 × Y × (1.337 − 0.1807*LN(0.863 × Y))	Scarlat et al. 2010
Barley	*Barley straw*	0.58 × 0.85 × Y × (1.38 − 0.2751 × LN(Y))	Scarlat et al. 2010
Rye	*Rye straw*	0.58 × 0.85 × Y × (1.5142 − 0.3007 × LN(0.866 × Y))	Scarlat et al. 2010
Oat	*Oat straw*	0.58 × 0.85 × Y × (1.3002 − 0.1874 × LN(0.879 × Y))	Scarlat et al. 2010
Triticale	*Triticale straw*	$0.58 \times 0.85 \times 2.125 \times Y^{0.6}$	(estimate for wheat)
Tomatoes	*Tomato crop residues (leaves and stems/tomato plant)*	3.5	Zotarelli et al. 2009
Grapes	*Branches and leaves*	2.9	Molina-Alcaide et al. 2008
Rape or colza seed	*Rapeseed straw*	0.50 × 0.60 × Y × (2.0475 − 0.452*LN(0.923 × Y))	García-Condado et al. 2019
Sunflower	*Sunflower stalks (straw)*	0.52 × 0.60 × Y × (3.2189 − 1.1097*LN(0.928 × Y))	Scarlat et al. 2010
Olives	*Olive tree pruning biomass*	0.574 × Y	Padilla- Rascón et al. 2020
	Olive leaves	0.063 × Y	Padilla- Rascón et al. 2020
	Olive pomace	0.226 x Y	Padilla- Rascón et al. 2020
	Olive stones	0.115 x Y	Padilla- Rascón et al. 2020
Potatoes	*Potato crop residues*	1.6831 + 0.1067 × Y	García-Condado et al. 2019
Rice	*Rice straw*	$1.7171 \times Y^{0.7933}$	García-Condado et al. 2019
Sugar beet	*Sugar beet leaves*	0.115 × 0.3266 × Y	Zwart et al. 2004, Krijnse Locker 2021, greenproteinproject.eu
	Sugar beet tops	0.279 × 0.1516 × Y	

Actual volumes of crop residues per country are determined through the formulas presented in Table 10, where crop areas and average yield are derived from Eurostat/FAOSTAT (values for 2021).

5.2 Estimations of volumes of secondary residues

Secondary residues are generated in processing. Their volumes cannot be directly estimated from crop production volumes in a country, because (a) most crops are used in diverse applications, and (b) crops may be traded between countries prior to processing. A more logical path is estimating the generated volumes of secondary residues from the main product volume. This approach requires estimates of volumes of the main products that resulted in the residue generation and heuristics for residue-to-volume ratios.

Table 11 summarizes estimations for residue-to-product factors (completed and updated compared to the heuristics presented in Agriloop deliverable D1.4).

TABLE 11. USED RESIDUE-TO-PRODUCT RATIOS: ASSUMED VOLUME OF RESIDUE (DRY MATTER WEIGHT) RELATIVE TO VOLUME OF PRODUCT (AS-IS WEIGHT).

Main product	Residue name	Residue-to-product ratio	Reference
Apple juice	*Apple pomace*	0.4 × 0.25	Estimated from Shalini et al. (2010), Turk et al. (2012), Vukusic et al. (2021
Beer	*Brewer's spent grain*	0.23 × 0.17	Mathias et al. 2015, Olajire (2020)
	Brewer's yeast	0.10 × 0.025	Fillaudeau et al. (2006)
Olive oil	*Olive pits (or stones)*	0.115 × 0.875 / 0.659	Padilla- Rascón et al. 2020
	Extractive Olive Pomace	0.226 × 0.875 / 0.659	Padilla- Rascón et al. 2020
	Olive oil vegetation water	Tbd	-
Peanut oil	*Peanut meal*	1.88	Nivtem (nd), Niftem (nda)
Peanuts	*Peanut skins*	0.04	Arya et al. (2016)
Potato starch	*Potato pulp*	0.1	Elbersen (2011)
Preprocessed potato[a]	*Potato peels*	0.123 × 0.09 / (1 − 0.09)	Arapoglou et al. 2010
Rapeseed oil	*Rapeseed hulls*	0.893 × 0.198 / 0.412	Carré et al. 2015
	Rapeseed meal	0.89 × 0.376 / 0.412	Carré et al. 2015
Rice bran oil	*Rice bran, defatted*	8	Estimated from lipids content of rice bran and defatted rice bran in Table 1.
Milled rice	*Rice husk*	0.28	http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products
	Rice bran	0.10	
Sugar	*Sugar beet pulp*	50 / 140	Estimated from Harmsen et al. (2014)
	Sugar beet molasses	0.6 × 40 / 140	Estimated from Harmsen et al. (2014)
Sunflower oil	*Sunflower meal*	1.15	Estimated from Le Clef et al. (2015)
Preserved tomatoes	*Tomato skins*	0.003	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Tomato juice	*Tomato pomace*	0.008	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Unconcentrated tomato paste and puree	*Tomato pomace*	0.008	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Concentrated tomato paste and puree	*Tomato pomace*	0.024[b]	Estimated from Del Valle et al. (2006) and Casa et al. (2021)
Wine	*Grape pomace*	0.0214	Ladakis e.a. (2020)
	Grape seeds	0.0064	Ladakis e.a. (2020)
	Grape stalks	0.0071	Ladakis e.a. (2020)

[a] *prepared potatoes, fries and other potato-derived snacks*

[b] *for concentrated tomato product an average concentration factor 3 is assumed*

Volumes of the main products produced per country (from which the residue volumes can be estimated based on the formulas presented in Table 11) were derived from diverse information sources (when available, average for the latest 3 years are used):

- Apple juice: Eurostat (for Europe) (may be inaccurate because these figures may include production of apple juice from imported concentrates).
- Beer: Eurostat (for European countries; average from most recent years for which data are provided) and www.china-briefing.com/news/chinas-beer-market-outlook-and-opportunities (for China).
- Olive oil: Eurostat (only for Europe).
- Peanut oil: production volume according to FAOSTAT (for Europe); www.indexmuni.com (for China; the higher value for China found in these data are considered more accurate than from FAOSTAT).
- Peanut skins: estimated from peanut food supply per country (FAOSTAT) (this may induce significant inaccuracies, but no better information source was found).
- Potato starch: Eurostat (for Europe); estimated from https://www.fnbnews.com/Top-News/global-potato-starch-market-trends-77501 (for China).
- Pre-processed potato: Eurostat (for Europe), https://potatoes.news/potato-processing-in-china-key-products/ (for China).
- Rapeseed oil: Estimated from volume of processed rape and mustard seed (assuming that the volume of mustard seeds can be neglected) per country (FAOSTAT), with estimated oil yield of 412 kg oil per ton seeds (Carré et al., 2015).
- Rice bran oil: guessed at 20% of the global market, which is 1.8 million tonnes per year (https://www.imarcgroup.com/rice-bran-oil-processing-plant). This is substantially higher than FAOSTAT data (which we consider less reliable).
- Milled rice: estimated from national production of paddy rice, assuming that milling is done in the country of rice production. A milling yield of 72% is assumed (derived from http://www.knowledgebank.irri.org/step-by-step-production/postharvest/rice-by-products).
- Sugar: Estimated from volume of processed sugar beets per country (FAOSTAT), with estimated yield of 140kg sugar per ton beets (Harmsen et al., 2014).
- Sunflower oil: Eurostat (for Europe), www.indexmundi.com (for China)
- Preserved tomatoes, tomato juice, unconcentrated tomato paste and puree and concentrated tomato paste and puree: Eurostat (for Europe).
  For China: no details of production volumes were found. As a work-around, the total volume of processed tomatoes was derived from www.indexmundi.com; next it was assumed that the subdivision over the product categories is equal as for Europe.
- Wine: agridata.ec.europa.eu (for Europe), https://www.oiv.int/sites/default/files/2024-04/oiv_state_of_the_world_vine_and_wine_sector_in_2023.pdf (for China).

6 Modelling and optimisation of valorisation pathways

As pointed out in previous chapters, estimates of volumes of crop residues, compositions of agricultural residues, and the yields of transformation products are continuously refined and updated as the AgriLoop project progresses. As more data become available, both from literature and experimental research within the AgriLoop consortium, it becomes essential to translate the findings to complete (biorefinery) processing pathways. Since in defining a biorefinery processing pathway many degrees of freedom exist (think of selection of specific unit operations, unit processes order, processing conditions, etc.) which may affect the actual yield of conversion and extraction processes, it is essential to identify optimised processing pathways. This comparison of different pathways is essential to identify which biorefinery designs are most promising for stakeholders that maximize or minimize specific objectives, such as economic returns and/or environmental benefits.

To address this goal, mathematical models are developed that represent the sequential transformation and separation of agricultural residues into valuable products. More specifically, a superstructure model can be generated which is essentially a conceptual map that includes all possible processing pathways and their interconnections. Each unit process (e.g., reactors or separation units) in the pathways is modelled in a generic way that represents possible actions that can take place, for example, mixing, separation emissions or reactions. The superstructure allows for a systematic evaluation of different design options and facilitates a comparison of alternatives to identify the most cost efficient, sustainable, or feasible solutions.

In order to accurately represent the superstructure model, comprehensive data is needed, which can be obtained from various sources such as literature reviews, experimental results from consortium partners, or inside knowledge from professionals in the field. This ensures that the models reflect real-world conditions and constraints as closely as possible. The contribution of this is thus essential to ensure an accurate model formulation.

The following sections will detail the methodology on how the superstructure optimization problems is formulated and used to optimize processing pathways of agricultural residue streams. This will be followed by a case study on potato peel to demonstrate the application of these methods. This case study will showcase how superstructure optimization can help in selecting the best valorisation pathway for transforming potato peel into added-value products.

By presenting these methodologies and real-world applications, the goal is to provide a clearer understanding of how superstructure optimization can drive decision-making in the valorisation of agricultural residues.

6.1 Methodology, superstructure optimization

6.1.1 Superstructure model

The superstructure optimization problem can be represented as a set of mathematical equations (Eq. 1-5) describing the objective and the different aspects of unit processes, such as mixing, chemical transformation, and logic rules responsible for the selection of a path in the process network:

$$\min(f(x,y)) \tag{1}$$

$$g(x,y) \geq 0 \tag{2}$$

$$h(x,y) = 0 \tag{3}$$

$$x^{LO} \leq x \leq x^{UP} \tag{4}$$

$$x \in X,\ y \in \{0;1\} \tag{5}$$

In these equations *f* is the objective function, for example the net emissions or production costs. The continuous variables, denoted by vector *x*, describe the operating variables (e.g., the flow of mass) within their respective lower and upper bounds x^{LO} and x^{UP}, in a continuous feasible region *X*. Vector *y* comprises binary variables, which is responsible for selecting a specific unit-process. *g* and *h* are the vectors of inequality and equality constraints, representing a series of possible operations that a unit process can carry out. These constraints are described by a set of generic equations for each process unit, representing the series of possible operations. For example, the mixing of various streams or the transformation and separation of mass.

The core set of equations to describe the superstructure model is based on the work of Kenkel et al. (2021), called OUTDOOR. This model is open source, written in Python, and easily modifiable. This flexibility allows for the incorporation of new modelling aspects, such as analysis under uncertainty, making it particularly suitable for our needs.

In OUTDOOR the generic Eq. (2) and (3) are used to describe 1) the mass balances of incoming and outgoing flows; 2) operating expenses from utilities like electricity, heating or cooling; 3) capital expenses of the unit operations; 4) basic environmental impacts such as CO_2 emissions and freshwater consumption; 5) heat exchange networks costs using a pinch analysis. The model is also capable of minimizing or maximizing several different objectives (Eq. (1)), such as the Earnings Before Income Tax (EBIT), the Net Production Costs (NPC), the Net Produced CO_2 Emissions (NPE) and the Fresh Water Consumption (FWC).

6.1.2 Modelling with Uncertainty

In process design, accounting for uncertainty is crucial to ensure robust and reliable operation under varying conditions. This section outlines the methods used to incorporate uncertainty in the superstructure optimization efforts.

6.1.2.1 Monte Carlo Simulations

One traditional method for addressing uncertainty is through Monte Carlo simulations. In this approach, multiple scenarios are generated with varying uncertain parameters, allowing the evaluation of the optimal design across a range of possible outcomes. This method offers insights into the variability of process performance (i.e., the objective function) and helps identify various potential optimal design configurations. As a result, it provides a solution that accounts for uncertainty as it unfolds, often referred to as the "wait-and-see" solution.

Monte Carlo simulations were conducted by sampling uncertain parameters using Latin Hypercube Sampling (LHS). A uniform distribution was applied to each set of sampled parameters to effectively cover the parameter space. Each set of parameters, representing a specific scenario, was sequentially simulated, producing a distribution of outputs that reflect various potential outcomes across all scenarios thereby highlighting possible risks and opportunities.

6.1.2.2 Two-Stage Stochastic Optimization

In a real-world setting, process design decisions – such as choosing which unit processes to use – must often be made before the uncertainties in the system are fully known. To optimize refinery design under these uncertain conditions, we use a method called two-stage stochastic optimization. This approach divides the decision-making into two types:

1. Here-and-Now decision variables: These are decisions that must be made before the uncertainties are revealed. They include key design choices like selecting unit processes and deciding how to allocate material (mass fractions) to different units.
2. Wait-and-See decision variables: These are decisions that can be adjusted once the uncertainties have been realized. They typically involve operational adjustments, such as modifying flow rates through the processes.

To solve this type of problem, we generate scenarios in a way similar to the Monte Carlo method, where a range of possible outcomes is simulated. However, unlike a typical Monte Carlo approach, the objective function in two-stage stochastic optimization considers all scenarios at once. The result is called the expected value of the objective, which represents an average outcome – such as expected yearly profit – over a long period of time.

The solution of the two-stage stochastic optimization problem provides the most robust design. This means that it accounts for uncertainties and fluctuating parameters, ensuring that the refinery design chosen before the uncertainties manifest will perform well across a range of possible future conditions.

6.1.3 Sensitivity Analysis

Sensitivity analysis provide insights into how variations in model parameters affect the outputs of a model. This section describes the sensitivity analysis methods employed in this study, highlighting both local and global approaches and for what they can be used for.

6.1.3.1 Local Sensitivity Analysis

The OUTDOOR software provides built-in tools for local sensitivity analysis, which involves adjusting one input parameter at a time while holding others constant. This method assesses how small changes in each parameter affect the model's output, offering insight into the sensitivity of the system to that parameter.

For example, applying local sensitivity analysis to the selling price of a product can reveal the price point at which that product becomes the most economically viable option compared to alternatives. This allows us to assess whether the production of a desired product can succeed within current market conditions or if further technological advancements are necessary. It also helps gauge whether market conditions might improve enough in the future to justify the investment.

While local sensitivity analysis can be useful for understanding the immediate impact of individual parameters, it has certain disadvantages. One major drawback is the difficulty in comparing the relative importance of parameters. This is because local sensitivity does not account for interactions between parameters and can be less informative in the context of complex, multi-parameter models.

6.1.3.2 Global Sensitivity Analysis

To overcome the limitations of local sensitivity analysis, a global sensitivity analysis was implemented into OUTDOOR using Standard Regression Coefficients (SRCs) calculated via the Monte Carlo procedure. This method provides a more comprehensive assessment by capturing the full range of variability and interactions between parameters. The SRCs quantify each parameter's relative importance in influencing model outcomes. For the results to be valid, the coefficient of determination (R^2) must exceed 0.7 for each output, indicating sufficient model linearity for reliable sensitivity assessment using SRCs (Helton and Davis, 2003).

This analysis is particularly useful for identifying potential process improvements. By calculating SRCs, users can pinpoint the most influential parameters affecting production costs in specific biorefinery designs, enabling targeted optimization efforts and guiding future research and development.

6.2 Case study: Optimal Valorisation pathways for potato peel residues

To better understand superstructure optimisation and the methodologies used to analyse them a case study will be presented focusing on the valorisation of potato peel.

6.2.1 Data collection and superstructure mapping

The construction of the superstructure (i.e., the mapping of processing units) and the necessary data to create the model, was obtained with the help of several different institutions from academia and Industry, primarily from the AgriLoop consortium, or from literature. The simplified superstructure containing all possible processing routes is presented in Figure 2. It explores both relatively novel valorisation pathways and more established processing routes for potato peel. The novel routes within the superstructure focus on the production of microbial protein for fish feed, polyhydroxyalkanoates (PHA) as a bioplastic alternative, and phenolic compounds as a food additive. In contrast, the more established routes include the production of starch, potato protein, and potato fibers, commonly used as supplements in the food industry. Other established options, such as the direct use of potato peels as animal feed, composting and anaerobic digestion were also considered. Additionally, the superstructure incorporates potential connections between these processing pathways exploring potential synergies or cascading designs.

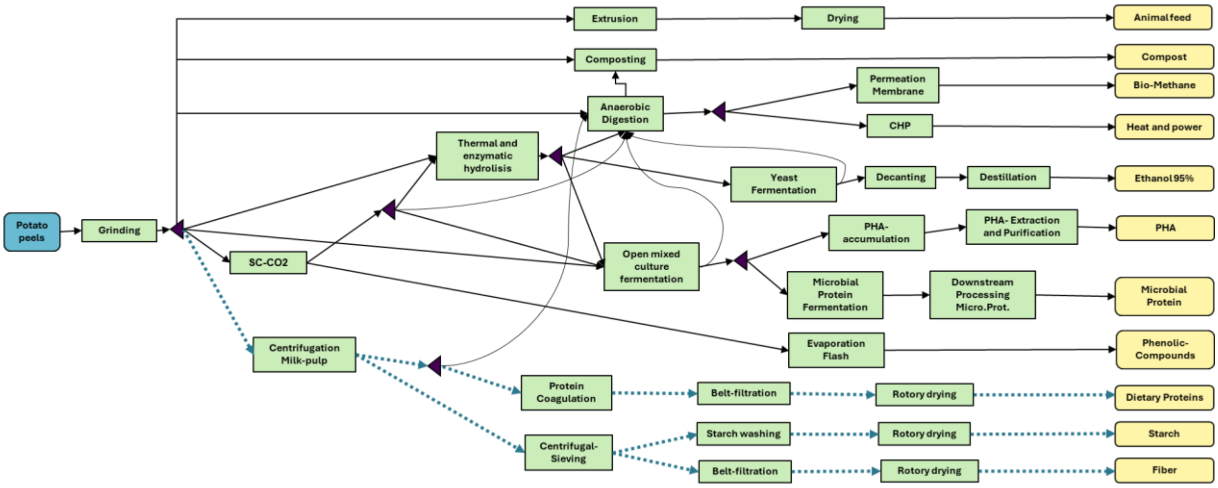

Figure 2. Simplified superstructure representing potential processing routes for valorising potato peel. Blue boxes represent inputs, green boxes denote unit processes, and yellow boxes correspond to final products. Triangles indicate decision points where process streams are split and routed to subsequent unit operations. Blue doted lines are production routes that are excluded in several optimisation efforts.

6.2.2 Optimization under assumed values

A single objective optimization problem, maximizing the EBIT, was run where average values of the parameters (i.e., data describing the unit processes) were assumed. In this manner the most economically feasible route was established, with the available assumptions of the current parameters and market conditions. Within OUTDOOR the superstructure optimization problem was formulated and solved using Gurobi (Gurobi Optimization LLC, 2024). The optimization problem converged to an optimal solution in 4.2 seconds with an optimality gap of 0. The computations were performed on a laptop with a 12th Gen Intel(R) Core(TM) i7-1255U, 1.70 GHz, 10 cores, 12 logical processors and 15 GB RAM.

The design solution from this optimization problem, shown in Figure 3, resulted in the production of starch, potato protein, and potato fibers – essentially forming a classic starch refinery as described by Phillips and Williams (2011). This refinery is designed to process up to 70 t/h of potato peel, producing 7.81 t/h of starch, 1.3 t/h of protein, and 3.69 t/h of fiber product. The calculated EBIT for this plant is 51.85 million €/year, which translates to a profit of 92 €/ton of potato peel. This is consistent with financial reports from Avebe, a leader in the potato starch industry, which reported a profit of 98 €/ton of potatoes in 2021 (Royal Avebe, 2022).

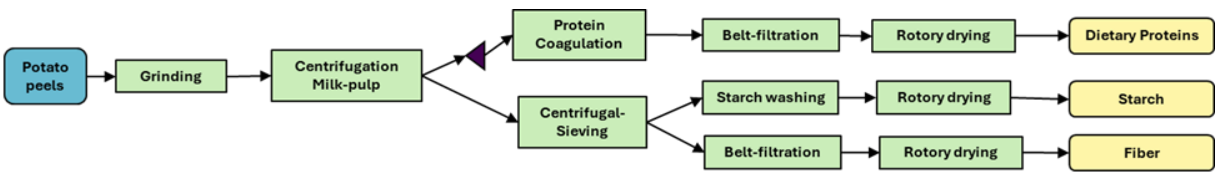

Figure 3. Design solution of the deterministic optimization problem producing starch, potato fibers, and potato proteins

Although this design, economically, far outperforms all other options in the superstructure, a reason for potentially excluding these production routes is the elevated concentrations of glycoalkaloids in the end products, which can be toxic for human consumption. Potato peels generally contain higher levels of glycoalkaloids, and these concentrations can vary depending on factors such as potato variety, storage conditions, and exposure to sunlight. Consequently, this processing pathway may not always be suitable for all types of potatoes or under every set of conditions (Schrenk et al., 2020).

To explore which other processing routes has the most potential aside from starch production, the superstructure optimization was rerun with starch and its byproducts excluded. When excluding starch production, the optimization now suggests that producing animal feed is the most economically viable option. This low-tech solution allows for the conversion of 70 t/h of potato peel into 13.7 t/h of animal feed (Figure 4). However, this design significantly underperforms compared to starch production, running at a loss of 0.61 million €/year or a loss of 1.09 €/ton of potato peel.

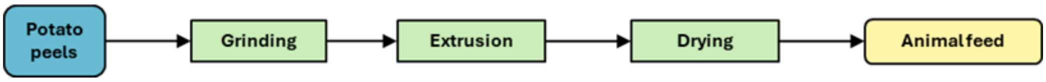

FIGURE 4. DESIGN SOLUTION OF THE DETERMINISTIC OPTIMIZATION PROBLEM ON THE REDUCED SUPERSTRUCTURE PRODUCING ANIMAL FEED.

While the production of animal feed appears to be the most promising design under the assumed conditions, it is important to acknowledge the uncertainties in the input data. For example, the composition of feedstock can vary significantly, and many of the technologies involved have a low Technological Readiness Level, are not fully optimized, or exhibit variable yields. Given these uncertainties, it is crucial to explore alternative design options and evaluate the associated risks and opportunities of other potentially viable designs.

6.2.3 Optimization under uncertainty: Montecarlo Simulations

To identify the most promising candidate designs under parameter uncertainty, Monte Carlo simulations were successfully performed. In this study, 200 scenarios, each with a different set of parameters, were considered. The optimal design for each scenario was solved sequentially using OUTDOOR and the Gurobi solver as detailed earlier. The scenarios were created by sampling the uncertain parameters with uniform distributions to comprehensively explore the design space. The uncertain parameters and their distribution ranges are presented in Table 12.

The solutions obtained from these scenarios represent the "wait and see" approach, which assumes that adjustments can be made to the plant design as soon as uncertainties become apparent. While this approach is not feasible in practical settings, it provides valuable insights into the processing routes with the highest potential. From the "wait and see" simulations, four alternative designs emerged as the most promising: the use of potato peels as animal feed, the production of bioplastic PHA, the production of microbial protein for fish feed, or composting the peels directly. The animal feed production design was optimal in 48.0 % of the scenarios, the bioplastic refinery in 8.5 %, the microbial protein design in 8.0 %, and the compost design 33.5 % of the time. Other hybrid designs were also suggested in 2 % of all the scenarios simulated, but due to their low frequency of occurrence, they will not be covered here.

To further analyse the four designs, each scenario where a design was not optimal was also simulated, reflecting the "here and now" solution. This approach assumes that the plant design is decided before the uncertainty is realized. By combining the "wait and see" and "here and now" results, Figure 5 was obtained. In Figure 5, The box plots indicate the EBIT distribution over all scenarios for each of the four designs corresponding to the results of the "here and now" solution, while the blue dots indicate the scenarios where the design was optimal according to the "wait and see" solution.

TABLE 12. UNCERTAIN PARAMETERS WITH THEIR MINIMUM AND MAXIMUM VALUES USED TO OPTIMIZE THE SUPERSTRUCTURE UNDER UNCERTAINTY AND STOCHASTICALLY.

Parameter	**Range**	**Unit process**	**Units**
Starch composition potato peels	[0.067 - 0.124]	Input, PPW	(-)
Phenolic composition potato peels	[0.01 - 0.03]	Input, PPW	(-)
Separation Efficiency, Phenolics	[0.081 - 0.189]	Super Critical CO2	(-)
Conversion Efficiency, Cellulose	[0.56 - 0.84]	Hydrolysis	(-)
Conversion Efficiency, Hemi-Cellulose	[0.56 - 0.83]	Hydrolysis	(-)
Stoichiometric Yield Ethanol	[0.45 - 0.55]	Ethanol Fermentation	(g_{EthOH}/g_{feed})
Stoichiometric Yield Microbial protein	[0.29 - 0.40]	Microbial Protein Fermentation	$(g_{Miro.Prot}/g_{feed})$
Conversion Efficiency Cellulose	[0.38 - 0.52]	Anaerobic Digestion	(-)
Yield $Biomass_{pha}$	[0.45 - 0.72]	PHA Accumulation	$(g_{feed}/g_{biomass})$
Stoichiometric Yield, PHA	[0.48 - 0.72]	PHA Recovery	$(g_{PHA}/g_{biomass})$
Stoichiometric Yield, VFA	[0.35 - 0.75]	Mixed Culture Fermentation	(g_{VFA}/g_{feed})
Separation Efficiency, PHA	[0.53 - 0.75]	Micro-Filtration	(-)
Heating Demand	[0.64 - 0.78]	Spray Drying PHA	kWh/kg
Electricity Price	[96.15 - 143.89]	n.a.	€/MWh
Material costs, Lysol	[57.28 - 85.79]	Input Lysol	€/ton
Product Price, Ethanol	[689.02 - 841.48]	Output Ethanol	€/ton
Product Price, Animal. Feed	[90.07 - 109.10]	Output Animal Feed	€/ton
Product Price, Microbial Protein	[1351.26 - 1649.74]	Output Microbial Protein	€/ton
Product Price PHA-Plastic	[2809.71 - 5199.18]	Output PHA	€/ton

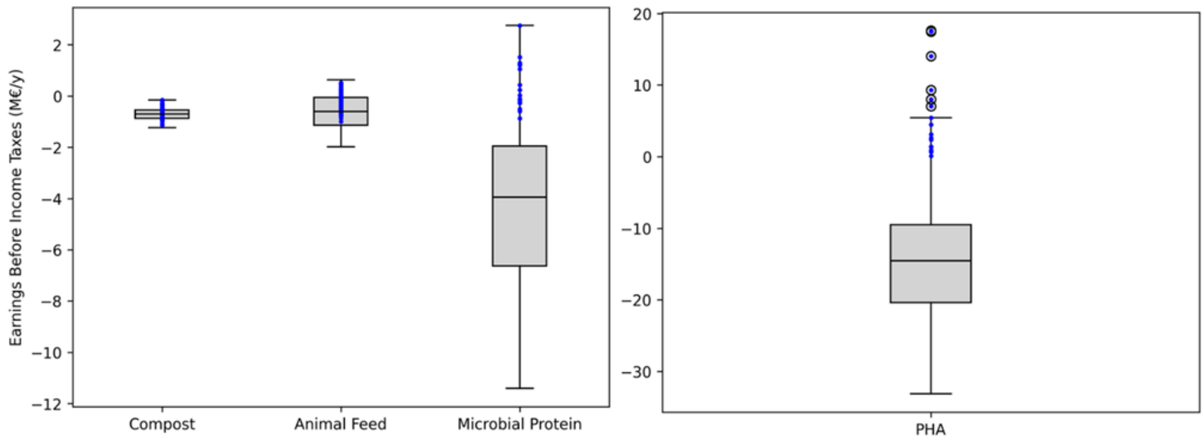

FIGURE 5. BOXPLOTS COMBINING THE OPTIMIZATION RESULTS OF THE "WAIT AND SEE" AND "HERE AND NOW" OPTIMIZATION PROBLEMS FOR EACH CONSIDERED DESIGN OBTAINED FROM THE WAIT AND SEE PROBLEM. THE BOXPLOTS REPRESENT THE "HERE AND NOW" SOLUTION PLOTTING THE DISTRIBUTION OF THE EARNINGS BEFORE INCOME TAX (EBIT) OVER ALL CONSIDERED SCENARIOS. THE DOTS REPRESENT WHERE THE SOLUTION WAS OPTIMAL IN THE "WAIT AND SEE" OPTIMIZATION PROBLEM.

Figure 5 shows that composting and animal feed production exhibit the least variation of the EBIT but also offer very narrow profit margins. In other words, while these options pose the least amount of financial risk in the face of uncertainty, they are also likely to result in little to no profit and may most likely run at a modest loss. Despite the low potential returns, the optimization still favours these solutions in a significant proportion of cases, with composting selected in 33% and animal feed production in 48% of all the simulated scenarios in the "wait and see" solution.

This preference can be attributed to the higher variability in the expected profits of microbial protein and PHA production, which are associated with greater uncertainty. As a result, these production routes were collectively only selected 16.5 % of the time. While designing the plant for microbial protein or PHA production offers the potential for substantial profits, it also comes with a much higher risk of financial loss, as seen in Figure 5. In that Figure it can also be seen that the solutions which are optimal in the "wait and see" solution (blue dots) fall in the upper quartile of the boxplot indicating that very favourable conditions need to arise for these processing routes to become the preferred design.

In summary, the choice comes down to a trade-off: opting for composting or animal feed provides a safer, more predictable outcome with a steady, albeit modest, loss. On the other hand, pursuing the riskier designs, such as microbial protein or PHA, presents the potential for significant profits but also carries the risk of substantial losses.

6.2.4 Optimization under uncertainty: Stochastic solution

In the previous section, four processing routes were proposed, each with a range of possible outcomes (Figure 5). To determine which of these four designs returns the most robust expected EBIT over the long term, a stochastic optimization problem was run. The same set of uncertain scenarios that were generated in Section 3.3. were used in the optimization problem. Furthermore, the variables selecting the unit processes and the variables determining the distribution of mass to various units were set as the first stage decision variables, ensuring that the optimization problem always selects the same units and splits the streams equivalently over all scenarios. The solution of the stochastic optimisation problem, favoured the design producing animal feed like Figure 3. The expected EBIT of the process design returns a loss of 0.63 million €/year which is a result very similar to the deterministic solution in Section 3.1. This expected EBIT can be seen as the average profit over a multi-year period, indicating a considerable loss of investment over time. This outcome suggests that, despite the negative expected profit, this design is more robust compared to others, which involve greater risk and have a higher potential for substantial losses. This result is in line with the solutions from the previous section where the designs for microbial protein and PHA production, were shown to have a larger potential to operate at greater losses.

6.2.5 Analysing processing routes for PHA production

The Monte Carlo simulations demonstrate that the processing routes for microbial protein and PHA production remain in a phase where profitability is uncertain (Figure 5). This highlights the need for significant technological advancements or favourable changes in market prices to make the production pathways of these value-added goods, economically viable.

Using the previously described methods of sensitivity analysis, specific processing routes of interest were further dissected and critically examined to determine the economic conditions or technological advancements necessary to make a particular route the most optimal, or at least more economically viable. In the following subsections, the approach to analysing the effects of selling prices and technological improvements will be detailed to produce PHA. This production route is particularly relevant for analysis, as plastic waste is a significant societal challenge, and an affordable, biodegradable alternative like PHA could have a substantial impact on the plastic market.

6.2.5.1 Optimal selling price

By applying a local sensitivity analysis to the selling price of PHA across the entire superstructure, excluding starch production and its by-products, it is possible to determine the price at which PHA becomes more competitive than other design alternatives. This analysis is based on the current technological capabilities of all processing routes. This selling price is found by graphically observing the incremental effects of the PHA price on the EBIT. I.e., as the selling price of PHA increases, the optimization problem shifts in favour of the PHA production route, at which point there is a linear increase in EBIT. The point where this linear increase begins marks the minimum selling price required for the production route of PHA to outperform alternative products. Figure 6 illustrates the relationship between PHA price and EBIT, showing that the optimal price to outcompete other products is approximately 6.22 €/kg. At this price the PHA biorefinery still operates at a loss of 1.08 €/ton of peels. However, at the price of 6.22 €/kg PHA, processing routes focusing on PHA surpasses the previous best design, producing animal feed as seen in the deterministic solution in Section 3.2.

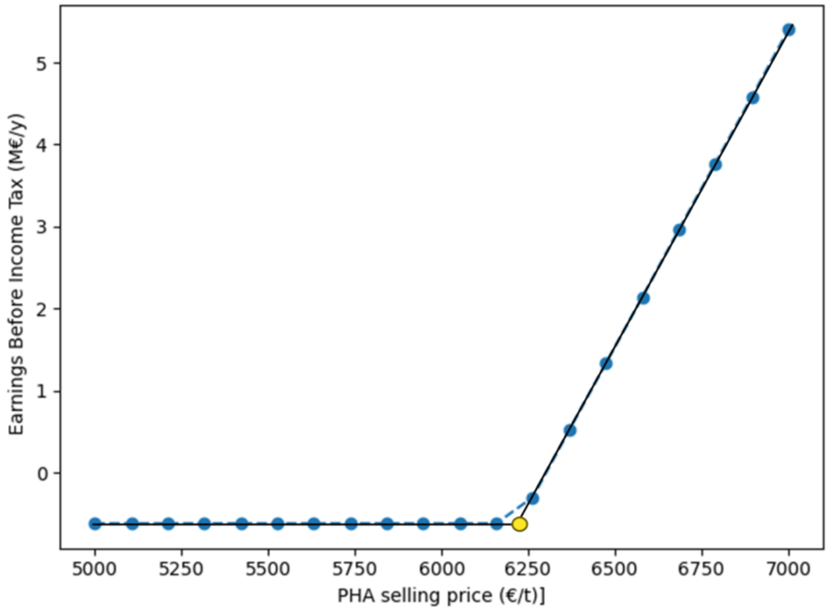

FIGURE 6. LOCAL SENSITIVITY ANALYSIS ON THE PRICE OF PHA ON THE REDUCED SUPERSTRUCTURE EXCLUDING STARCH PRODUCTION AND BY PRODUCTS. THE YELLOW DOT INDICATES WHERE THE SELLING PRICE OF PHA MAKE THE PRODUCTION ROUTE OF PHA THE MOST OPTIMAL.

6.2.5.2 Covering production costs

The previous section determined that the price to sell PHA, to out compete other alternative products, still runs at a loss. To determine the minimum price at which PHA needs to be sold to cover production costs, an optimization problem was formulated using a superstructure limited to the processing routes for PHA production, with the objective function modified to minimize net production costs. Details of the reduced PHA superstructure and the objective function formulation can be found in Supplementary Materials S1 and S2 of Van der Hauwaert (2025). Applying this optimization to the reduced superstructure, focused on the production of PHA, it was found that the minimal selling price required for the plant to recover costs is 7.11 €/kg. This value falls within the upper range of estimated production costs for PHA, which typically range from 2 to 8 €/kg (Fernández-Dacosta et al., 2015). The higher production cost in this case could be attributed to the handling of solid waste (e.g., biomass sludge) which is forced through the anaerobic digestion and composting units.

The average selling price assumed for PHA in the optimization was 4.5 €/kg. This means that the process only becomes profitable with an overhead price of 2.61 €/kg. Given that conventional plastics like PET have a production cost of around 1.5 €/kg, hoping for markets to change in favour of PHA seems rather unlikely. In other words, it is clear that there is still significant room for improvement in reducing PHA production costs on an industrial scale, at least with the current design proposed in the superstructure.

6.2.6 Finding technological improvements

Assuming that the market is ready to purchase bioplastic at a price of 4.5 €/kg, the most relevant technological improvements to the process design were identified by calculating the SRCs on the previous reduced superstructure, focusing on the production of PHA. The parameters considered, along with their respective ranges, are detailed in Table 13, alongside the corresponding SRC values for each parameter. The R2 value, which measures the proportion of variance in the EBIT explained by the parameters, was calculated to be 0.88, indicating that the SRCs provides a reliable comparison of the parameters.

TABLE 13. PARAMETERS USED FOR THE GLOBAL SENSITIVITY ANALYSIS, THE CONSIDERED RANGES OF THE UNCERTAIN PARAMETERS AND THE REPORTED SRC.

Parameter	Unit Process	Range	Units	SRC
Stoichiometric Yield	PHA Recovery	[0.30 - 0.89]	($g_{PHA}/g_{Biomass}$)	0.61
Separation Efficiency	Micro-Filtration	[0.32 - 0.95]	(-)	0.59
Yield	PHA Accumulation	[0.29 - 0.88]	(g_{PHA}/g_{VFA})	0.32
Material costs, Lysol	Input Lysol	[57.35 - 85.73]	€/ton	0.15
Stoichiometric Yield	Mix. culture Ferm.	[0.28 - 0.82]	(g_{VFA}/g_{feed})	0.15
Starch composition Feed	Input potato peels	[0.06 - 0.13]	(-)	0.06
Electricity Price	n.a.	[96.27 - 143.82]	€/MWh	0.01
Heating Demand	Spray Drying PHA	[0.36 - 1.06]	kWh/kg	0.01

From Table 13, it is evident that the yield of PHA from biomass in the PHA Recovery unit, is the most influential parameter affecting the EBIT, with an SRC of 0.61. The second most influential parameter, with an SRC of 0.59, is the separation efficiency of the microfiltration unit, that separates PHA from the broth leaving the PHA Recovery unit. These two parameters are critical to improving the economic viability of the PHA production pathway.

To better understand the effects of these two parameters on the EBIT a cross-sensitivity analysis was performed. From the cross sensitivity a contour plot was made (Figure 7) where the interaction between PHA yields and separation efficiency on the overall EBIT can be observed. The contour plot illustrates how different combinations of these two key parameters impact the economic performance of the process, with the EBIT shown as contour levels across the parameter space. The 0-Euros EBIT contour line, represented by the solid cyan line, is of particular importance as it indicates the threshold at which the processing pathway transitions from a loss to a break-even point. Currently, the yield of PHA from biomass is assumed to be 0.63 g PHA per g biomass, while the separation efficiency of PHA from the broth is estimated to be around 0.65, as shown by the yellow dot in Figure 7. The closest point on the 0-Euro EBIT line, determined by the shortest Euclidean distance to the current technological parameters, corresponds to a yield of 0.71 in the PHA recovery unit and a separation efficiency of 0.74 in the microfiltration unit. This indicates that the yield must increase by 0.08, and the separation efficiency by 0.09. These improvements are feasible, suggesting that efforts should focus on enhancing these two parameters to significantly boost the profitability of PHA production.

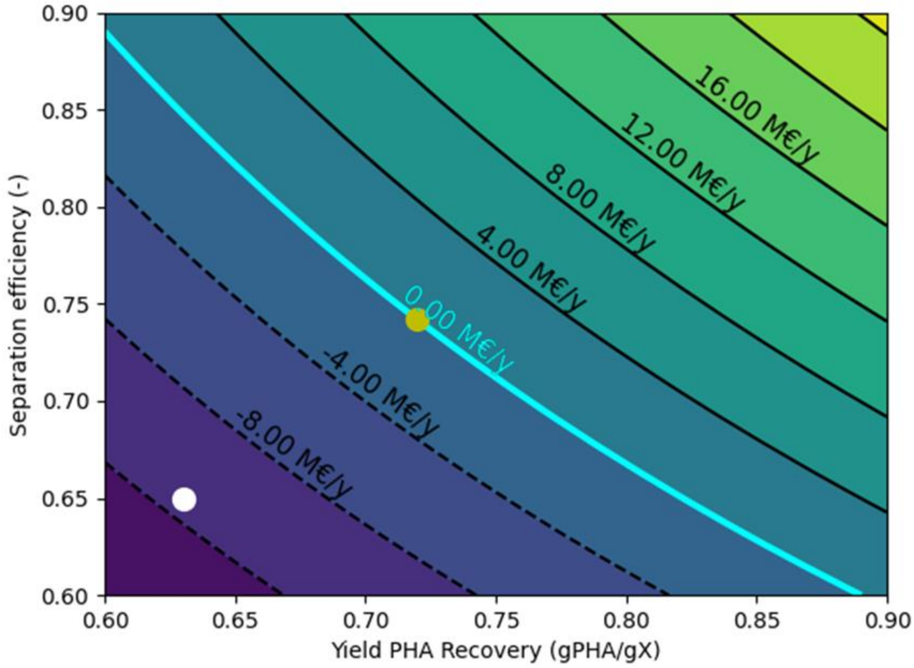

FIGURE 7. CONTOUR PLOT OF THE CROSS-SENSITIVITY ANALYSIS SHOWING THE IMPACT OF THE RECOVERY YIELD (GPHA/GBIOMASS) (X-AXIS) AND MICROFILTRATION SEPARATION EFFICIENCY (Y-AXIS) ON THE EARNING BEFORE INCOME TAXES (EBIT) IN M€/Y. THE WHITE DOT REPRESENTS CURRENT TECHNOLOGY LEVELS, CYAN LINE REPRESENTS WHERE COSTS ARE RECOVERED (EBIT = 0) WHILE THE YELLOW DOT REPRESENTS THE CLOSEST POINT OF THE CURRENT LEVEL OF THE TECHNOLOGIES TO THE 0 €/Y LINE.

6.3 Conclusions of the modelling framework

In this chapter the concept of a superstructure was reviewed – a comprehensive framework that maps out all potential processes and pathways for converting agricultural residues into valuable products. This included an exploration of the types of optimization problems that can be formulated within this framework, as well as the analyses available to identify optimal design choices.

These methods were then applied to a case study for the AgriLoop project, specifically examining the valorization of potato peel. The optimization objective was to determine the best design from a techno-economic perspective. Initial findings indicated that while starch production was the most profitable pathway, it is recommended to take in consideration potential toxicity of the products. Further analysis, excluding starch production, highlighted animal feed as the most robust solution for managing potato peel, even under uncertain conditions.

Additionally, production pathways for PHA (polyhydroxyalkanoates), a promising biodegradable plastic, were examined to identify technological bottlenecks. Addressing these bottlenecks could significantly improve the economic feasibility of PHA production. This framework thus allows for the recommendation of the most promising early-stage designs and highlights areas where technological advancements are most needed to improve economic viability.

Looking forward, it is essential that future assessments consider not only profitability but also sustainability metrics. A balanced approach that incorporates both economic and environmental factors will support the development of processes that are financially sound and ecologically responsible, creating lasting value for both industry and society.

7 Conclusions

In this report a methodology, heuristics and essential data were presented for early estimating potential yields from selected agro-residue streams to biopolymers, proteins and some other relevant products. This method is based on:

- estimates of macro-nutrient compositions per residue stream,
- heuristics for early/approximate estimates of conversion/extraction yields to diverse biobased and protein products, based on literature-derived yield factors linked to the macro-nutrient composition per residue stream,
- estimates of volumes of selected agri-residues streams in EU per country, UK and CN.

Compared to Agriloop deliverable D1.4 lacking compositional data were added and the set of residue streams was extended (including relevant streams for CN). Furthermore, the set of described conversion pathways was extended with a selection of biopolymers and protein extraction pathways. Additionally, the estimates for volumes of agri-residue streams were updated based on a critical comparison of estimates presented in D1.4 with some practical values; also estimates of the volumes for the added residue streams were added.

Furthermore, a methodology for early estimating environmental impact of processing/application pathways was developed. Two indicators are addressed: circularity (indicator for resource use efficiency) and climate impact (indicator for sustainability impact). An essential feature of this method is the scope: next to the main product (e.g. protein product or biopolymer) also side-streams that are generated in the process should be taken in consideration. Including that functionality, the methodology was elaborated (heuristics, parameters) for a subset of the processing/application pathways for which the potential yields are presented. The heuristics were elaborated in an excel-based calculator – as for the yields of processing to proteins and other products – which facilitates rapid assessments of valorisation pathways based on a residue-stream's composition. In order to make comparisons with common valorisation pathways (like feed or land application), also these reference application pathways are described in the method.

From first case studies with the method for early environmental impact assessment, some preliminary general conclusions were drawn:

- Adequate combination of material – processing pathway – product application is essential for efficiency and environmental sustainability. Generated results confirm, for instance, that residue streams with relatively high protein content are more suited for protein extraction (or use as animal feed), whereas residue streams with high content of (simple) carbohydrates are more suited for producing biopolymers or other biobased applications.
- Although the utilisation of a residue stream is considered sustainable, energy use in intensive processing can have relatively large negative impact on the environmental

sustainability of a processing route/application. This was illustrated for extracting rubisco proteins from sugar beet leaves. Preliminary assumed energy use in the extraction and further processing (estimated from one reference) results in higher GHG emission intensity of the rubisco protein product than a reference protein product considered (soybean protein isolate). From this observation it is concluded that making choices regarding the processing route, the impact of the (process) chain must also be taken into account.
Note: the comparison of rubisco protein with soybean protein isolate overlooks functional differences between both products; it is recommended to extend the comparison with protein sources that are more similar. The example of rubisco protein extraction was provided here in order to show the relevancy of addressing all aspects of the pathway from residue to products.

The next step in developing early estimates of yields and environmental impact of biopolymer and protein production from residues is estimating parameters for the processing pathways explored in the technical research in the Agriloop project (Agriloop WPs 2, 3 and 4). For that, insights in processing steps (as explored in the technical research) must be translated to complete (biorefinery) processing pathways. Since in defining a biorefinery processing pathway many degrees of freedom exist (think of selection of specific unit operations, unit processes order, processing conditions, etc.) which may affect the actual yield of conversion and extraction processes, it is essential to identify optimised processing pathways. Analysing and comparing diverse pathways is essential to identify which biorefinery designs are most promising for stakeholders that maximize or minimize specific objectives, such as economic returns and/or environmental benefits. For that, a modelling framework was developed and demonstrated on potato peels.

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N°	Dataset name	Open Data	Closed Data	Means of dissemination	Maximum delay before access	Data set access
1	WP1.2_WR_JB	Estimates of volumes of agri-residues streams, their composition and potential yields to protein, biopolymers and other biobased products	-	Scientific and popularized publications, conferences, various dissemination and capacity-building events. Will be updated and enhanced with sustainability estimates in D1..6	Once published and at the latest 2 years after the end of the project	

Above table above sums up the main information regarding the data produced for this deliverable, where is it stored and are the specific rules to respect concerning access, publication and FAIR principles.

N°	Dataset name	Owner	Name of the current contact	PR issues	Use of third-party	Restrictions on data sharing (Y/N)
1	WP1.2_WR_JB	WR	Jan Broeze	-	no	N

Above table above sums up the main information regarding potential Intellectual property protection or GDPR issues.

Annex 1. Estimated extraction and conversion yields to biopolymers and proteins

TABLE 14. ESTIMATES OF YIELDS FROM SELECTED AGRI-RESIDUE STREAMS TO BIOBASED PRODUCTS AND PROTEINS (KG PRODUCT PER TON RESIDUE STREAM)

Agri-residue stream	Bio-methane	Bio-ethanol	Bio-diesel	PHA/PHB	Bio-PE	Bio-PET	PEF	PLA	Protein extraction based on hydrolysis	RuBisCo protein extraction
Apple pomace	192.0	279.7	37.8	39.5	16.7	12.4	33.5	46.5	47.6	20.4
Barley straw	168.0	284.8	12.6	13.2	5.2	4.2	11.2	15.0	26.6	11.4
Brewer's spent grain	234.6	212.0	82.8	46.3	8.6	7.1	19.0	24.9	175.2	75.1
Brewer's yeast	267.8	176.6	75.6	74.3	26.9	22.5	60.9	78.9	267.8	114.8
Broken rice	255.6	436.1	7.2	256.7	145.4	127.6	344.6	435.8	54.6	23.4
DDGS from maize	262.4	213.1	112.5	60.7	10.4	8.5	23.0	30.2	187.6	80.4
DDGS from wheat	242.1	196.0	61.2	47.3	15.4	11.7	31.7	43.4	226.8	97.2
Discolored rice	226.1	370.2	18.0	208.6	115.7	101.3	273.6	346.4	54.6	23.4
Grape branches and leaves	168.8	277.2	15.3	14.3	5.2	4.2	11.2	15.0	32.2	13.8
Grape pomace	148.6	192.6	0.0	63.1	41.9	31.6	85.2	117.3	103.5	44.4
Grape seeds	163.0	134.1	102.6	43.2	1.9	1.7	4.5	5.7	63.4	27.2
Maize (corn) stover	178.9	287.3	16.2	14.6	5.2	4.2	11.2	15.0	47.6	20.4
Molasses	231.4	382.7	1.8	205.5	138.2	102.4	276.5	384.0	68.6	29.4
Oat straw	170.3	284.5	14.6	22.4	10.8	8.4	22.6	30.7	27.0	11.6
Olive pomace	165.4	194.9	37.8	31.9	11.6	8.6	23.2	32.3	86.1	36.9
Olive pruning branches	158.7	255.7	0.0	0.0	0.0	0.0	0.0	0.0	54.6	23.4
Olive pruning leaves	154.7	239.2	0.0	0.0	0.0	0.0	0.0	0.0	68.6	29.4
Olive stones	336.0	212.8	273.6	113.8	4.2	3.7	10.0	12.6	120.4	51.6
Peanut meal	264.7	172.0	12.2	100.2	60.3	47.9	129.2	172.7	356.7	152.9
Peanut skins	268.4	190.5	179.3	143.9	43.7	37.3	100.6	129.3	114.5	49.1
Potato crop residues	141.2	189.7	17.1	26.7	13.0	10.1	27.2	36.8	51.2	21.9
Potato peels	236.3	364.6	8.6	176.1	99.4	86.9	234.5	297.2	88.6	38.0
Potato peels	236.3	364.6	8.6	176.1	99.4	86.9	234.5	297.2	88.6	38.0
Potato pulp (starch industry)	202.8	338.7	1.9	77.9	44.6	38.8	104.8	133.1	66.6	28.5
Rapeseed hulls	210.6	159.3	118.8	77.6	19.0	15.8	42.6	55.5	112.7	48.3

Agri-residue stream	Bio-methane	Bio-ethanol	Bio-diesel	PHA/PHB	Bio-PE	Bio-PET	PEF	PLA	Protein extraction based on hydrolysis	RuBisCo protein extraction
Rapeseed meal	226.8	172.0	21.6	56.0	31.6	23.8	64.3	88.4	266.7	114.3
Rapeseed straw	167.5	249.8	12.6	10.8	3.8	2.9	7.9	10.8	39.9	17.1
Rice bran	244.9	248.5	124.0	153.0	61.0	52.7	142.2	181.4	88.4	37.9
Rice bran, defatted	193.0	256.2	29.7	106.3	55.2	47.6	128.6	164.1	92.9	39.8
Rice husk	137.5	227.6	0.0	18.6	10.6	9.3	25.2	31.8	25.9	11.1
Rice straw	153.5	251.9	12.6	13.2	5.2	4.2	11.2	15.0	29.4	12.6
Rye straw	165.7	273.8	12.6	13.2	5.2	4.2	11.2	15.0	28.7	12.3
Sugar beet leaves	193.3	227.2	21.9	88.6	52.4	40.1	108.1	147.5	136.6	58.5
Sugar beet pulp	192.6	321.2	7.2	27.5	16.3	12.4	33.4	45.8	57.4	24.6
Sunflower meal	205.3	186.4	0.0	24.4	16.5	12.2	32.9	45.8	226.8	97.2
Sunflower straw	168.0	257.1	12.6	13.2	5.2	4.2	11.2	15.0	51.1	21.9
Tomato crop residues	168.8	277.2	15.3	14.3	5.2	4.2	11.2	15.0	32.2	13.8
Tomato pomace	204.9	128.9	107.1	41.7	0.0	0.0	0.0	0.0	147.0	63.0
Tomato pomace	204.9	128.9	107.1	41.7	0.0	0.0	0.0	0.0	147.0	63.0
Tomato pomace	204.9	128.9	107.1	41.7	0.0	0.0	0.0	0.0	147.0	63.0
Tomato skins	122.8	113.9	27.9	10.9	0.0	0.0	0.0	0.0	83.3	35.7
Triticale straw	234.6	212.0	82.8	46.3	8.6	7.1	19.0	24.9	175.2	75.1
Unripe rice	226.1	370.2	18.0	208.6	115.7	101.3	273.6	346.4	54.6	23.4
Wheat straw	171.2	274.6	13.8	17.6	7.7	6.2	16.6	22.1	31.5	13.5

Annex 2. Estimated volumes of selected agri-residues streams per country

Estimations of volumes of selected agri-residues streams, as explained in chapter 5, are presented in below tables.

TABLE 15. ESTIMATED VOLUMES OF CROP RESIDUES FROM CEREALS INCLUDING RICE

	Wheat straw	Maize (corn) stover	Barley straw	Rye straw	Oat straw	Triticale straw	Rice straw
Total EU27	72,090,372	32,391,299	24,253,127	4,457,824	4,287,586	6,733,968	0
Belgium	750,923	193,505	120,260	1,894	8,457	16,030	0
Bulgaria	3,735,046	1,597,501	314,805	10,974	13,840	34,806	72,090
Croatia	483,242	997,214	139,185	1,176	31,990	24,507	0
Cyprus	20,007	0	15,018	0	201	983	0
Czechia	2,485,667	422,315	791,664	66,867	105,274	108,809	0
Denmark	1,891,070	20,486	1,548,379	334,309	167,778	23,441	0
Estonia	439,073	0	206,032	24,810	45,867	17,102	0
Finland	450,093	0	570,517	38,878	454,716	5,864	0
France	17,658,410	6,530,607	4,816,005	105,890	246,865	946,122	76,186
Germany	10,149,714	1,881,490	4,382,120	1,734,069	396,785	988,879	0
Greece	759,498	560,370	177,180	11,777	46,241	27,257	281,498
Hungary	2,720,106	2,985,012	734,246	50,197	42,141	159,488	12,618
Ireland	261,152	0	594,933	0	105,502	0	0
Italy	4,294,211	2,564,993	525,397	6,615	136,949	35,577	1,705,769
Latvia	1,384,376	0	115,686	78,639	106,901	15,916	0
Lithuania	2,438,871	48,969	256,142	40,376	101,548	143,735	0
Luxembourg	39,175	211	13,059	3,762	3,543	13,995	0
Malta	0	0	0	0	0	0	0
Netherlands	431,562	72,815	83,291	4,539	3,631	3,178	0
Norway	156,826	0	295,354	21,008	141,645	0	0
Poland	6,558,276	3,292,016	1,446,927	1,467,016	892,091	3,164,396	0
Portugal	51,060	318,799	26,403	12,320	24,884	18,316	208,617
Romania	5,837,948	6,944,671	948,808	21,413	119,948	155,724	20,863
Slovenia	80,291	167,033	53,630	1,427	2,220	14,381	0
Slovakia	1,052,369	702,547	272,853	20,923	21,179	19,747	0
Spain	5,141,123	1,858,875	4,666,800	196,449	684,677	535,794	702,913
Sweden	1,517,272	6,512	524,752	73,642	299,001	83,309	0
United Kingdom	6,438,733	0	3,034,599	107,211	554,204	36,354	0
China	70,127,195	121,375,453	1,002,514	311,102	319,530	301,194	242,736,505

TABLE 16. ESTIMATED VOLUMES OF CROP RESIDUES FROM OTHER CROPS THAN CEREALS

	Olive pruning branches	Olive pruning leaves	Tomato crop residues	Grape branches and leaves	Sunflower straw	Rapeseed straw	Potato crop residues	Sugar beet leaves
Total EU27	6,872,072	754,252	809,862	9,048,058	7,584,883	7,937,062	7,799,558	4,256,161
Belgium	0	0	2,205	1,624	0	12,868	564,430	170,892
Bulgaria	0	0	10,745	82,737	1,457,549	181,141	39,221	0
Croatia	13,701	1,504	1,015	61,509	80,304	37,078	28,434	26,554
Cyprus	9,729	1,068	875	17,864	0	0	16,162	0
Czechia	0	0	910	47,444	34,487	488,289	110,096	155,684
Denmark	0	0	105	0	0	284,354	347,960	96,643
Estonia	0	0	35	0	0	105,534	12,305	0
Finland	0	0	315	0	0	24,726	93,840	15,135
France	15,819	1,736	21,665	2,197,707	1,303,248	1,521,760	1,315,064	1,290,730
Germany	0	0	1,400	292,059	69,683	1,595,239	1,641,746	1,199,837
Greece	0	0	45,990	260,536	161,080	5,466	61,535	1,080
Hungary	0	0	6,790	171,303	1,209,714	354,600	40,352	25,465
Ireland	0	0	35	0	0	21,474	58,510	0
Italy	1,303,342	143,050	357,210	2,037,743	204,757	26,055	223,940	56,741
Latvia	0	0	0	0	0	205,649	24,568	0
Lithuania	0	0	2,520	0	0	435,944	47,159	32,168
Luxembourg	0	0	0	3,567	230	2,162	2,791	0
Malta	11	1	0	1,334	0	0	1,719	0
Netherlands	0	0	6,475	551	0	2,085	979,966	246,235
Norway	0	0	137	0	0	4,019	58,913	0
Poland	0	0	26,950	2,900	24,354	1,442,973	1,152,517	573,671
Portugal	789,681	86,672	62,230	509,298	7,997	0	72,377	0
Romania	0	0	63,455	474,469	2,015,508	649,601	291,422	29,429
Slovenia	528	58	735	43,210	780	3,476	11,428	317
Slovakia	0	0	840	22,475	135,676	199,904	26,339	51,245
Spain	4,739,260	520,163	196,385	2,695,231	739,207	118,364	328,561	94,134
Sweden	0	0	140	261	0	159,940	128,108	76,868
United Kingdom	0	0	683	1,322	0	458,701	54,939,719	276,584
China	0	0	3,992,506	2,256,084	1,810,881	7,399,926	19,630,078	450,107

TABLE 17. ESTIMATED VOLUMES OF SECONDARY RESIDUES (1)

	DDGS from wheat	DDGS from maize	Brewer's spent grain	Brewer's yeast	Potato peels	Potato pulp (starch industry)	Sugar beet pulp	Molasses
Total EU27	1,637,362	3,188,895	1,284,214	82,111	127,516	126,293	4,834,067	2,320,352

	DDGS from wheat	DDGS from maize	Brewer's spent grain	Brewer's yeast	Potato peels	Potato pulp (starch industry)	Sugar beet pulp	Molasses
Belgium	106,116	206,669	1,284,214	82,111	46,413	0	221,033	106,096
Bulgaria	32,719	63,723	17,417	1,114	41	0	0	0
Croatia	0	0	10,016	640	0	0	36,817	17,672
Cyprus	0	0	0	0	0	0	0	0
Czechia	34,311	66,823	71,865	4,595	0	1,943	197,000	94,560
Denmark	0	0	20,650	1,320	25	25,022	117,117	56,216
Estonia	3,891	7,578	5,454	349	0	0	0	0
Finland	12,380	24,111	14,509	928	198	0	18,967	9,104
France	355,487	692,340	80,666	5,158	0	0	1,285,033	616,816
Germany	199,320	388,192	295,257	18,878	12,596	41,646	1,362,100	653,808
Greece	5,306	10,333	17,974	1,149	0	0	1,417	680
Hungary	197,552	384,748	21,025	1,344	3	0	30,300	14,544
Ireland	1,769	3,444	6,261	400	0	0	0	0
Italy	26,706	52,012	61,408	3,926	43	194	70,083	33,640
Latvia	4,598	8,956	3,056	195	0	0	0	0
Lithuania	5,659	11,022	12,841	821	0	0	42,667	20,480
Luxembourg	0	0	0	0	0	0	0	0
Malta	0	0	0	0	0	0	0	0
Netherlands	132,644	258,336	97,347	6,224	40,636	23,218	328,483	157,672
Norway	0	0	9,673	618	497	0	0	0
Poland	71,097	138,468	148,390	9,488	5,582	18,198	725,567	348,272
Portugal	531	1,033	29,040	1,857	41	0	0	0
Romania	2,122	4,133	66,143	4,229	0	0	27,467	13,184
Slovenia	0	0	0	0	0	0	0	0
Slovakia	38,025	74,056	7,149	457	0	53	56,817	27,272
Spain	105,585	205,635	142,254	9,096	7	0	93,733	44,992
Sweden	73,397	142,946	18,979	1,214	272	1,503	94,067	45,152
United Kingdom	182,165	354,781	1,470,160	94,000	9,873	1,453	269,950	129,576
China	816,774	1,590,734	1,407,600	90,000	9,099	40,487	340,000	163,200

TABLE 18. ESTIMATED VOLUMES OF SECONDARY RESIDUES (2)

	Rapeseed meal	Rapeseed hulls	Sunflower meal
Total EU27	7,443,398	3,932,874	3,895,308

	Rapeseed meal	Rapeseed hulls	Sunflower meal
Belgium	446,967	236,165	434
Bulgaria	21,975	11,611	809,546
Croatia	17,959	9,489	12,571
Cyprus	0	0	0
Czechia	360,073	190,252	0
Denmark	224,209	118,465	289
Estonia	50,977	26,935	0
Finland	44,842	23,693	0
France	1,398,907	739,141	617,953
Germany	3,058,610	1,616,080	73,506
Greece	5,354	2,829	62,269
Hungary	84,887	44,852	437,281
Ireland	10,151	5,363	0
Italy	20,971	11,080	104,350
Latvia	48,746	25,756	0
Lithuania	77,636	41,021	5,841
Luxembourg	0	0	0
Malta	0	0	0
Netherlands	0	0	0
Norway	3,458	1,827	0
Poland	1,004,812	530,914	0
Portugal	50,531	26,699	20,342
Romania	133,187	70,372	221,065
Slovenia	223	118	0
Slovakia	75,406	39,842	0
Spain	72,617	38,369	84,652
Sweden	113,889	60,176	0
United Kingdom	539,105	284,847	0
China	2,565,127	1,355,338	506,000

TABLE 19. ESTIMATED VOLUMES OF SECONDARY RESIDUES (1)

	Apple pomace	Olive pomace	Olive stones	Tomato skins	Tomato pomace (from juice)	Tomato pomace (from unconcentrated puree)	Tomato pomace (from concentrated puree)	Grape pomace	Grape seeds
Total EU27	197,938	510,175	259,602	7,607	997	9,998	27,053	340,160	101,730
Belgium	3,407	0	0	0	0	0	0	0	0
Bulgaria	623	0	0	10	0	10	122	1,598	478
Croatia	78	1,052	535	0	0	0	182	1,200	359
Cyprus	0	0	0	0	0	0	0	232	69
Czechia	1,059	0	0	0	0	16	27	1,227	367
Denmark	2,781	0	0	0	6	0	0	0	0

	Apple pomace	Olive pomace	Olive stones	Tomato skins	Tomato pomace (from juice)	Tomato pomace (from unconcentrated puree)	Tomato pomace (from concentrated puree)	Grape pomace	Grape seeds
Estonia	152	0	0	0	16	0	0	0	0
Finland	1,615	0	0	0	0	0	0	0	0
France	14,756	1,383	704	41	96	333	246	94,921	28,388
Germany	66,930	0	0	1	172	0	0	18,299	5,473
Greece	626	73,269	37,283	173	0	193	1,085	4,459	1,334
Hungary	6,632	0	0	0	26	0	363	5,325	1,593
Ireland	0	0	0	0	0	0	0	0	0
Italy	9,694	89,417	45,500	6,291	54	7,766	7,424	106,663	31,899
Latvia	0	0	0	0	0	0	0	0	0
Lithuania	428	0	0	23	17	0	0	0	0
Luxembourg	0	0	0	0	0	0	0	184	55
Malta	0	0	0	0	0	0	0	32	9
Netherlands	5,739	0	0	0	33	0	1	21	6
Norway	2,418	0	0	0	0	0	0	0	0
Poland	61,236	0	0	78	345	1	981	0	0
Portugal	914	48,227	24,540	84	0	1,074	6,501	13,818	4,133
Romania	901	0	0	4	0	22	302	8,323	2,489
Slovenia	0	149	76	0	0	0	0	1,169	350
Slovakia	0	0	0	0	0	0	0	709	212
Spain	12,635	295,805	150,520	896	39	729	9,386	76,571	22,900
Sweden	2,293	0	0	0	0	0	3	0	0
United Kingdom	18,000	0	0	0	0	0	0	0	0
China	0	0	0	8,346	1,094	10,969	29,680	6,848	2,048

	Peanut meal	**Peanut skins**	**Rice husk**	**Rice bran**	**Rice bran, defatted**
Total EU27	0	0	0	0	0
Belgium	12,533	213	0	0	0
Bulgaria	0	680	11,624	4,359	0
Croatia	0	400	0	0	0
Cyprus	0	0	0	0	0
Czechia	1,880	1,293	0	0	0
Denmark	1,880	547	0	0	0
Estonia	0	100	0	0	0
Finland	0	787	0	0	0
France	0	11,787	12,468	4,676	0
Germany	0	8,013	0	0	0

Greece	8,147	200	49,068	18,401	0
Hungary	0	187	1,904	714	0
Ireland	0	1,187	0	0	0
Italy	8,773	1,707	291,862	109,448	0
Latvia	0	107	0	0	0
Lithuania	0	187	0	0	0
Luxembourg	0	40	0	0	0
Malta	0	80	0	0	0
Netherlands	0	1,147	0	0	0
Norway	0	933	0	0	0
Poland	36,347	427	0	0	0
Portugal	6,267	240	35,180	13,193	0
Romania	0	1,307	2,996	1,124	0
Slovenia	0	213	0	0	0
Slovakia	0	333	0	0	0
Spain	0	3,587	123,436	46,289	0
Sweden	0	2,053	0	0	0
United Kingdom	0	7,827	0	0	0
China	6,016,000	409,693	42,372,000	15,889,500	2,880,000

Annex 3. Estimating GHG emission effect of products generated from agri-residues

(Co-)product/ destination/ function	Described effect in GHG emission effect accounting	Rationale for replacement ratio[a]	Estimated GHG emissions associated to unit replacement product
Food	Considered functionalities of food are protein supply and nutritional energy supply. Proteins generated from an agri-residue are considered to replace soybean protein isolate. Nutritional energy in the product is considered to replace wheat starch.	Based on protein content of soybean protein isolate (~90%) and nutritional energy content of wheat starch. Both have dry matter content ~90%.	Soybean protein isolate: 8.76 kg CO2e/kg Wheat starch: 0.69 kg CO2e/kg (carboncloud.com[9])
Fertilizer: N	Replaces synthetic fertilizer N	Average effectiveness of N from organic fertilizer compared to synthetic fertilizers (Schröder et al., 2019): • for crop residues 35% • for manure and digestate 80%	N in synthetic fertilizers: 3 kg CO2e/kg (Vidovic e.a., 2023)
Fertilizer: persistent organic matter	Estimated GWP100 effect of carbon sequestration in the soil	-	Lignin: -0.7 kg CO2e/kg Cellulose: -0.10 kg CO2e/kg Hemicellulose: -0.07kg CO2e/kg (further elaboration of Broeze et al., 2024)
Feed	Replaces a combination of wheat and soybean meal in feed (ratio depending on the materials' protein content and feeding energy content)	Estimated from protein content and estimated feed energy content	Wheat: 0.44 kg CO2e/kg Soybean meal: 2.0 kg CO2e/kg (GFLI, 2022: values for RER (Europe), EF3.1, economic allocation)
Food	Replaces a combination of wheat and soybean protein isolate in food (ratio depending on the materials' protein content and nutritional energy content)	Estimated from protein content and estimated nutritional energy content	Wheat: 0.63 kg CO2e/kg Soybean protein isolate: 8.76 kg CO2e/kg (values for food ingredient in Europe, CarbonCloud.com)
Biogas	Replaces natural gas	Based on combustion heat of produced bio-methane	0.067 kg CO2e/MJ (Koffi et al., 2017)
Digestate	As described above for • Fertilizer: N • Fertilizer: persistent organic matter		
Bioethanol	Replaces (fossil) petrol	1 kg bioethanol replaces 1 kg fossil petrol	4.14 kg CO2e/kg (includes upstream GHG emissions)
PHA/PHB	Replaces fossil-derived plastics	1 kg PHA/PHB replaces 1 kg of fossil-derived plastics	~ 3 kg CO2e/kg (varies amongst types of plastic) (ETC/WMGE, 2021)

[a] Ratio replacement product : residue-derived product

[9] Accessed 18 October 2024.